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# Neck Injury Criteria Development for Use in System Level Ejection Testing; Characterization of ATD to Human Response Correlation under -Gx Accelerative Input

Craig M. Zinck

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THESIS

Craig M. Zinck, Captain, USAF

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**DEPARTMENT OF THE AIR FORCE**
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## AIR FORCE INSTITUTE OF TECHNOLOGY

**Wright-Patterson Air Force Base, Ohio**

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Craig M. Zinck, MBA

Captain, USAF

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Craig M. Zinck, MBA

Captain, USAF


Committee Membership:

Lt Col Jeffrey C. Parr, PhD

Chair

Michael E. Miller, PhD

Member

Chris Perry, MS

Member

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## Abstract

The use of Helmet Mounted Displays is becoming ubiquitous in the field of aviation, adding operational capability while increasing head-supported weight and potential neck injury risk during ejection. Developing neck injury criteria to evaluate and quantify neck injury risk is important to ensure ejection systems are produced within acceptable safety standards. In this study, an ATD to human transfer function for is developed that quantifies the difference between Anthropomorphic Test Device (ATD) and human neck response data from -Gx accelerative tests, and demonstrates how this transfer function can be applied to ATD test data to make previously developed human risk functions directly applicable to interpreting the ATD data with a human-based neck injury criterion. To gain an understanding of how the MANIC(Gx) can be applied to escape system testing, the ATD test values were evaluated using the current state of the art MANIC(Gx) human risk curves. A difference between the human and ATD MANIC(Gx) neck response was measurable, the ATD indicated lower MANIC(Gx) levels at equivalent AIS risk probabilities. For instance, at 5% probability of neck injury risk, the ATD MANIC(Gx) (for AIS 2+ and AIS 3+ probability of injury) values were 0.29 and 0.364 respectively where the human values at the same injury percentage was 0.56 and 0.72. The associated injury criteria can be directly applied to ATD safety testing of aircraft ejection or vehicles systems in -Gx accelerative loading to directly translate ATD neck load results to the probability of human injury.

## Acknowledgments

I would like to express immense gratitude to all of my fellow students for their encouragement and assistance during my time at AFIT, I would not have made it without many of you. I would also like to thank my committee members and my advisor for their unwavering guidance throughout this program.  Mostly, I would like to thank my amazing wife and kids for the sacrifices that they have made over the past 18 months in order for me to succeed in this endeavor; I love you all so very much.

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# Neck Injury Criteria Development for Use in System Level Ejection Testing; Characterization of ATD to Human Response Correlation Under -Gx Accelerative Input

## I. Introduction

### Background

Manned aircraft of the future will certainly utilize Helmet Mounted Device (HMD) technologies in an effort to ensure they are state-of-the-art; maintaining their operational high-ground. HMDs provide a pilot with an interface that requires less visual scanning, resulting in reduced object capture time, and increased user efficiency. Incorporation of HMDs replaces legacy displays with in-visor instrument displays along with other operationally relevant information such as radio frequencies, weapon data, threat data, and flight safety warnings. A focus on Human Systems Integration is imperative when designing systems that are intended to work in-concert with the user (Parr 2014; Rash et al. 2009). Supporting additional head-borne mass may be an effective use of pilot resources, but also may negatively affect performance if the weight change is enough to hinder operational ability. The additional weight of HMDs must be evaluated so that the potential benefits and injury risks can be quantified in order for the decision maker to have clarity of action when deciding on HMD alternatives. Designing escape systems that opt to use HMD hardware to increase performance while adding significant head-supported weight has presented the U.S. Air Force (USAF) with a unique personnel safety issue.

Escape systems incorporated into the design of fighter aircraft are integral to ensuring pilot safety.  Safety is of utmost importance to the USAF, the escape system developers, and the pilots who operate these weapon systems.  Neck injury evaluation related to the function of escape systems, particularly with added HMD weight, has been a topic for many years.  In 1995 a phase one Small Business Innovative Research (SBIR) defined the need for a human injury prediction tool that could be used to correlate manikin to human neck response when under accelerative load (Grierson and Dunn, 1995); therefore, a significant amount of HMD development effort should be dedicated to acquiring safe escape system equipment.  This research intends to provide decision makers with a method that enables developmental testing in the -Gx plane of accelerative input to be accomplished using Anthropometric Test Devices (ATD) but with a human-based neck injury criterion supported by a quantitative risk functions.

Limiting injuries by creating relevant design requirements is the goal of the USAF, however, a logical methodology for creating HMD requirements focused on pilot safety has proven difficult to quantify.  There has been incongruence between acceptable and unacceptable testing conditions when using existent criteria.  A more quantitative method of escape system evaluation is required for better informed decision making that is founded on quantified human injury risk.  There have been designs that fail to meet all requirements, yet when a SME qualitative analysis deems that the limit excursions are negligible or "within tolerance" they are ushered through.  Current helmet device design limitations consist of weight and center of gravity (CG) restrictions imposed by an interim criterion called the Knox Box, developed 21 years ago, long before the advancement of current HMD designs.  However, development of the Knox Box assumed a single ejection seat with a known range of accelerations and a specific range of airspeeds, which affect forces due to windblast.  The complex relationship between helmet, ejection seat, and airspeed parameters makes the development of easily-measured helmet requirements difficult to specify without overly restricting the design trade space.

Rather than specifying specific helmet characteristics, system level requirements can be developed and enforced against the prime contractor to permit trades in helmet characteristics, ejection system characteristics and ejection procedures.  These system level requirements can provide system requirements to be demonstrated during system verification and validation.  Multiple neck injury criteria have been used in aviation, focusing on a wide range of accelerative input conditions that mimic specific portions of forces absorbed by a pilot during ejection.  Focus areas of these previous studies include characterizing head and neck biomechanics, tensile and bending neck strength characterization, injury classification, lower neck, upper neck, and finally multi-axial neck criteria development (Eppinger et al. 1999; Parr et al. 2013; Parr, 2014; FAA, 2011; Parr et al., 2015)

Numerous neck injury criteria will be briefly explained in the following literature review, to establish the history of neck injury study and its application to aviation.  The Knox Box, developed by USAF ejection researchers (Perry, Buhrman, & Knox III, 1993) was an effort to provide guidance to Air Force Research Laboratory (AFRL) personnel who were developing HMD prototype designs. The Knox Box permits helmets having a range of mass and CG values as its primary metrics, creating a virtual box that all HMD prototype designs should fall within. The idea behind the Knox Box was to limit the weight and off-axis moment (CG) to minimize chances of pilot injury. This criterion was developed as an early design guideline, not intended for long-term use in HMD development efforts however, it is still being utilized as the starting point for HMD design (Parr et al., 2014).

The US Navy and Air Force developed a 12-part Neck Injury Criterion (NIC) that was developed by using instrumented aerospace ATDs of varying sizes configured with Hybrid III necks. Those ATDs were then subjected to sled test ejections at different equivalent airspeeds (Nichols, 2006). The NIC provides criteria that can indicate limit overages however, after SME review these excursions are sometimes waived and the test is given a pass. Essentially, no definite or quantitative pass fail criteria are adhered to within the NIC, and none of the twelve elements of the NIC are supported by adequate human neck injury risk functions (Parr et al., 2014).

All of the aforementioned aviation studies have moved the USAF research and operational testing communities toward finding an escape system evaluation tool, however, there are still areas that need improvement. In 2009 the Air Force Life Cycle Management Center (AFLCMC) escape system oversight office requested the development of an improved criterion for evaluating pilot neck injury risk using a multi-axial evaluation tool that accounts for occupant size and is based upon human neck injury data. Parr implemented a previously proposed pilot-scale neck injury criterion called the multi-axial neck injury criterion (MANIC), that is relevant to and developed for evaluating neck injury risk in the aviation environment. However, further investigation in each axis (Gx, Gy, and Gz) is required to verify the use of the MANIC in developmental testing with ATDs. This research will investigate how the human and ATD neck response to acceleration level relate to one another using -Gx input forces similar to frontal impact (coronal plane force).

During initial prototyping, an HMD system is unable to be thoroughly tested in an operationally representative environment (Parr, 2014). The field of aviation neck injury biomechanics seeks to provide more information about weight and center of gravity restrictions, how these design considerations affect the human neck, and how to incorporate these considerations into future helmet design prior to prototyping. The current method used in the USAF to assess the design of prototype helmets is the Knox Box, a method that was intended as a temporary tool. Even though it is considered a temporary tool, the Knox box provides boundaries for design teams early in the process. If these bounds were imposed on helmet design teams after prototyping has begun, the cost repercussions would be much more severe. Only after the HMD is technologically mature can it be tested on ATDs using sled test ejections at the escape system level (including ejection seat and pilot ensemble). The cost of system level testing can be prohibitive; this creates a need for a well-defined neck injury criterion that can be used to alleviate redesign later in a design programs life cycle. Having the ability to use the results from a system level ATD ejection sled test for human injury prediction would be valuable to all stakeholders involved.

Parr (2014) attempted to account for the discrepancies in the above methods and fulfill the updated neck injury requirements set forth by AFLCMC. Parr's research resulted in the development of the MANIC, which sought to include all six major forces and moments that could be observed in the upper neck as a result of accelerative loading in the three primary axes of acceleration (Gx, Gy, and Gz).  The MANIC complies with AFLCMCs multi-axial neck injury criteria requirement and is defined in Equation 1. Multi-Axial Neck Injury Criteria (Parr, 2014)

**Equation 1. Multi-Axial Neck Injury Criteria (Parr, 2014)**

$$MANIC = \sqrt{\left(\frac{Fx}{Fxcrit}\right)^2 + \left(\frac{Fy}{Fycrit}\right)^2 + \left(\frac{Fz}{Fzcrit}\right)^2 + \left(\frac{Mx}{Mxcrit}\right)^2 + \left(\frac{My}{Mycrit}\right)^2 + \left(\frac{Mz}{Mzcrit}\right)^2}$$

The MANIC is a robust evaluation tool that is directly linked to associated human injury through generation and analysis of human risk functions .  This criterion fulfills all of the requirements imposed by the AFLCMC; no other neck injury metric/criterion developed to date does this.

This research intends to provide decision makers with a method for using ATD test results as an indicator of human injury  during developmental testing when exposed to similar -Gx accelerative input. The proposed method will be accomplished using existing human-based MANIC(Gx) quantitative risk functions.

## Problem Statement

Historically, the use of ATDs with instrumented necks, Post Mortem Human Subjects (PMHS), and porcine subjects have been accelerated to levels that would be injurious to humans in order to quantify the injury possibilities associated with individual test setup parameters (Cheng et al., 1986; Bass et al., 2006; Salzar et al. 2009; Beeman et al. 2013; Eppinger et al., 1999). Human testing has limitations, accelerating human subjects to a potential condition of known injury is unethical. Impact testing with human subjects has acceleration magnitude limits (for example, 10G in the z-axis) in order to keep potential injury of test volunteers minimized. The creation of a human to ATD transfer function and the development of new comparison methods for human and ATD -Gx accelerative loading results to quantify neck injury risk to aircrew is the intent of this research. Providing information that affords systems engineers the foundation to define and generate valid, traceable requirements to future HMD designs based on ATD data will save time, coordination and cost. Leveraging past research efforts is essential for success in this endeavor. By using the current aviation specific MANIC criteria and its associated MANIC(Gx) human risk curves, this research will concentrate on the frontal plane (coronal) forces for development of a -Gx ATD to human transfer function. The following research questions will be explored in this thesis effort:

1) What is the difference in expected MANIC(Gx) between human/PMHS and ATDs over the range of -Gx accelerative input observed from previous laboratory experiments?

2) Can the observed differences in peak MANIC(Gx) be used to create a transfer function to make the Parr et al. human-based risk functions and associated neck injury criterion more appropriate for use in testing with ATDs?

Defining injury parameters that are directly linked to validated human risk curves will provide HMD developers a metric to refine their designs.

**Justification**

In 2000 the Chief of Staff of the Air Force (CSAF) initiated acceptance of a congressional mandate that was previously approved to allowed females to fly fighter aircraft by expansion of ejection seat weight ranges resulting in lowering the low limit from 132 lbs. to 103 lbs. and expanding the upper limit from 211 lbs. to 245 lbs. (Personal Communication, 2014). Incorporation of additional head supported weight in the form of HMD technology and expanded weight ranges ensure that future weapons systems have the best available equipment and best available aircrew in future weapon platforms. However, a current weapon platform undergoing the acquisition process, the F-35, has elected to make a safety decision and limit pilot weights to above 136 lbs., eliminating the pilot pool below this limit due to increased injury potential.

Aircraft escape systems are integral to the safety of aircrew. Any redesign in these systems could drive schedule slip, aircraft availability issues and create an operational disadvantage. If these re-designs are due to escape system safety concerns, a more exhaustive engineering effort to fix the error will increase costs and leave a temporary gap in operational capability. Systems engineering principles have shown that early funding decisions are the most critical, any changes (re-design) late in the program can cause severe budget overrun (US DoD, 2013).

The added weight of HMDs is also a concern, particularly for the smaller aviator. Generation II HMDs add 2.19 lbs. of head supported weight to the standard helmet, and the F-35 Generation III designs add 2.60 lbs. These HMD weight increases make up a larger proportion of head supported weight for pilots at the small end of the anthropometric range (Perry, 1999). By widening the acceptable weight range, the USAF accepted a higher risk for aircrew below 136 lbs., by proxy. According to current USAF guidance; future escape systems and any associated equipment should not increase the current risk of pilot injury.. The associated risks, by body weight, for USAF F-35 ejections are depicted in Figure 1, this graphic depicts hazard risk index (HRI) as a function of aircrew weight and ejection air speed measured in knots equivalent airspeed (KEAS). These accepted risks directly affect over 33 percent of the female pilot population (Meyer & Andries, 2014).

The creation of a human to ATD transfer function will be used for the development of a method to link ATD test results to human injury likelihood using previously developed human neck injury risk functions at specific injury levels that are applicable to all weight ranges. This will enable decision makers to justify concrete escape system requirements by providing them with quantitative injury risk data in the prototyping and developmental testing process, allowing all stakeholders involved to accurately create, test, and certify HMDs and escape systems.

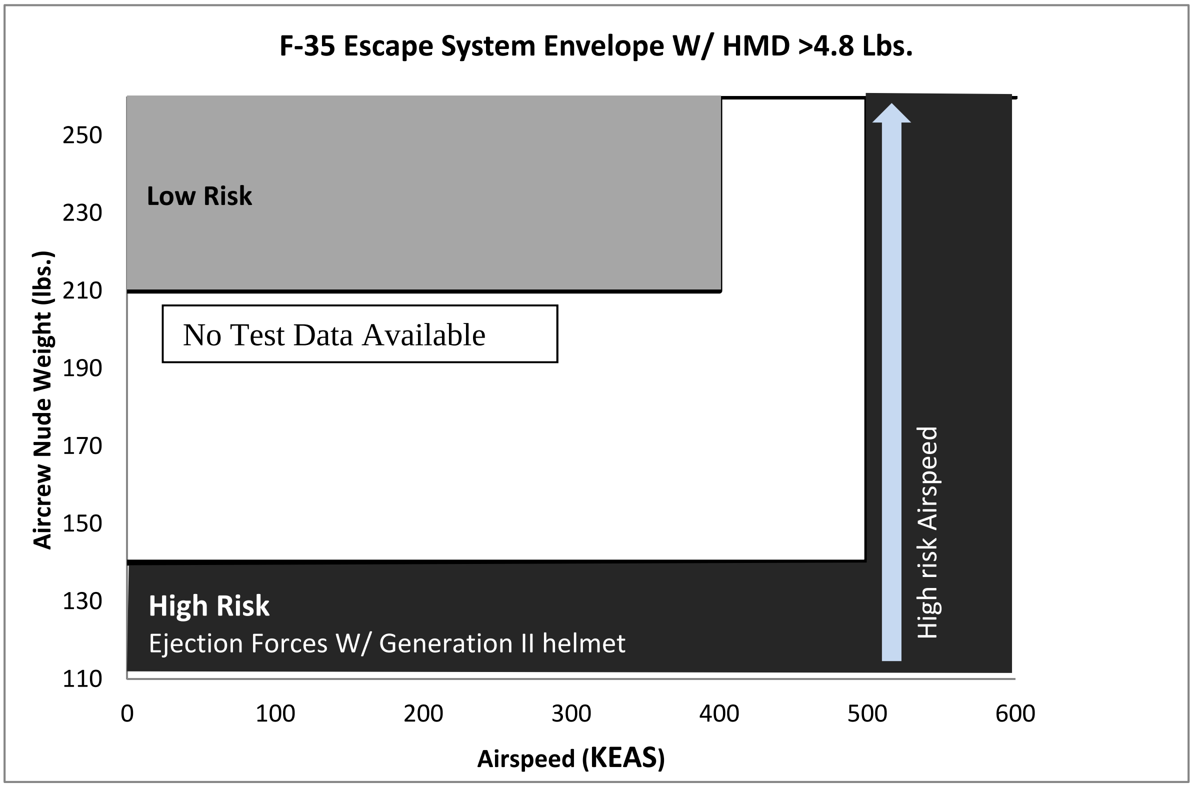


**Figure 1. F-35 HMD Ejection Risks vs. Body Weight**

## Thesis Outline

This thesis is structured in the scholarly format. Chapter 1 provides an overview of the research topic, research questions, and motivation. Chapter 2 provides a literature review of the pertinent scholarly research in the field of neck injury criteria and injury biomechanics. Chapter 3 is a conference paper that has been accepted for presentation at the 2016 Industrial and Systems Engineering Research Conference (ISERC). This ISERC paper documents the first phase of the research conducted in this thesis effort to develop a transfer function based on existing data from previous human and ATD -Gx accelerative tests. Chapter 4 is a journal article to be submitted to the Journal of Aerospace Medicine and Human Performance (called the Journal of Aviation, Space, and Environmental Medicine prior to January 2015). It documents the complete research effort undertaken in this thesis, starting with the -Gx human to ATD transfer function development, followed by the application of this human to ATD transfer function to calculate new ATD-transferred human risk probabilities using the previously developed human MANIC(Gx) risk functions that allow for evaluation of escape system neck injury risk due to -Gx acceleration directly with ATDs. Chapter 5 provides a summary and conclusions of the thesis research.

**Assumptions/Limitations**

Although the AFLCMC escape system oversight office requirement is to create neck injury criteria that are multi-axial, a human-based, ATD-transformed neck injury criterion in a single plane of motion will be used as a proof of concept. Future research will concentrate on the other critical planes of accelerative input (Gy and Gz). A transfer function to predict likelihood of ejection neck injury is based on the correlation of ATD neck response to that of human subjects. In past research it has been shown that ATDs neck response gets progressively more flexible when accelerative loads are applied when compared to PMHS response at high G levels (Beeman et al., 2013). The assumption that human muscle responds relatively similar to this stiffness under loading is required to ensure that data can be compared between the two populations across a wide range of -Gx accelerative input (up to 45 G's). Parr's pilot-scale, human-based MANIC risk functions and associated neck injury criteria had to make the assumption that human neck response was approximately equal to ATD neck response to apply the MANIC injury risk limits to testing with ATDs (Parr, 2014). This work seeks to investigate Parr's assumption and attempt to make the -Gx portion of Parr's MANIC more applicable to testing with ATDs. Future work will require additional ATD testing to validate the applicability of the transfer functions created here for use in the systems level ejection environment. Additionally, any helmet design requirements or restrictions that can be gleaned from this data should conform to the Air Force requirement generation protocols listed in the Defense Acquisition Guidebook (DAG). Finally, the evaluation of chronic injury due to neck loading caused by HMD use will not be covered in this research.

**Expected Contributions**

The transfer functions and MANIC(Gx) risk functions used in this work will be applicable for use in military safety testing applications that experience x-axis accelerations and may be applicable to the automotive or other industries where head supported weight is a requirement.

## II. Literature Review

### Introduction

Biomechanics of the neck when subjected to accelerative loading has been studied by multiple organizations, including The National Highway Traffic Safety Administration (NHTSA), the Federal Aviation Administration, academic research institutions and the Department of Defense (DoD) (Buhrman and Perry, 1994; Bass et al., 2006; Eppinger et al., 1999; Parr et al., 2013; Parr 2014;Parr, 2015; Salzar et al., 2009). The automotive industry (NHTSA) research efforts were some of the first to attempt to characterize the effects of accelerative loading on human neck by testing surrogate subjects. The testing of PMHS, porcine subjects, and ATDs all played a part of the initial testing, evaluation, neck injury classification, and injury criterion creation. This chapter will serve as a background for the research to be conducted in this thesis as well outline other contributions that are relevant to this research.

The DoD adopted some of the practices that were set forth in the automotive realm and adapted those practices in an attempt to characterize human neck response during ejection. Multiple neck injury criteria have since been developed to quantify neck loading and will be addressed in this chapter. It has proven difficult to extend the automotive centered analysis to human risk during ejection. Among the difficulties is the fact that the NHTSA has been most concerned about accelerations resulting from frontal impact crashes and therefore has concentrated their efforts to quantify the risk to vehicle occupants due to forces in the Gx plane, while pilots can experience substantial force in combinations of all three axes during the ejection sequence. Injury probability and classification of injury severity during ejection are the stakeholder level metrics used to quantify the risks future pilots might incur during ejection from an aircraft and are therefore important to project during acceptance testing of any DoD aircraft. These anticipated risks must be scalable and reliable across a wide range of pilot anthropometry as well as statistically sound, reliable, and quantitative in nature. Injury criteria and quantification protocols that are useable at escape system level accelerations are the anticipated end goal of DoD neck injury biomechanics research. Engineering decomposition and analysis of the problem in each force vector may lead to development of functional pieces of a complete human based escape system evaluation tool that can be aggregated, or used as stand-alone vector specific criteria.

Risk curve development is aimed at specifying a likelihood of injury based on input factors (neck size, HMD weight, HMD CG, injury classification) and loading of a pilot's neck. A test manager or decision authority will be able to use the developed risk curves and make a critical safety decision early in development based on quantitative analysis, ideally prior to incurring the substantial costs of live ejection testing in the developmental and validation testing phases.

## Head and Neck Anatomy and Biomechanics

"The neck and spinal cord system could be the most complicated human physiology aspect to evaluate during crash impact" (Mertz, 1971)

The ability to use an Anthropomorphic Test Device (ATD) in crash tests allows the test agency to subject the ATD to forces that could not be applied to humans due to the risk of human injury.  For this reason, military test agencies have used the ATD to test and qualify escape systems since the inception of the ejection seat.  ATD capabilities have been improved since the first ATD testing took place, and new neck components have been developed to mimic the movements and forces present in the human neck under loading. A more human representative neck called the Hybrid III was originally developed by General Motors and adopted for use in frontal impact studies by the NHTSA (Rasmussen & Plaga, 1993).  Some have postulated that the Hybrid III neck under loading is much stiffer than a PMHS neck under similar loads and therefore is not a biofidelic representation of human neck response (Myers et al.,1991, Bass et al., 2006). Due to the observed differences in human and PMHS versus ATD neck response, this research attempts to construct a model that links ATD and human neck response.  ATDs have been the best surrogate available for mimicking human response in operational testing at higher accelerative levels. A test agency should be able to use an ATD and predict how the resultant ATD data would affect a human in similar conditions. Unfortunately, this has proven difficult in the extremely dynamic aviation environment with ejection seat equipped aircraft.

Upper neck loads are the focus in the aviation domain since the lower neck has more muscle mass surrounding the area and the vertebrae are relatively larger.  Previous testing has indicated upper neck injury when PMHS are subjected to frontal impact (Mertz et al., 1978).  The upper neck critical values are lower and more injuries have been observed in this area than in the lower neck as addressed in previous human and PMHS testing (Nichols, 2006).  Figure 2 depicts the cervical section of the spine (C1-

C7). The upper neck area is defined by the location where the Occipital Condyle (OC), the base of the skull, and the atlas (C1) vertebrae connect (Grierson and Dunn, 1995). This connection provides the ability to articulate the head forward and backward at the base of the skull (Flexion and Extension).  A vertebra called the axis (C2) connects below the atlas via a bony projection called the dens (Odontoid Process) and provides the ability of left and right rotation.  The remaining Neck vertebrae provide the neck the ability to move in flexion, extension and, lateral bending with minor rotational allowances.

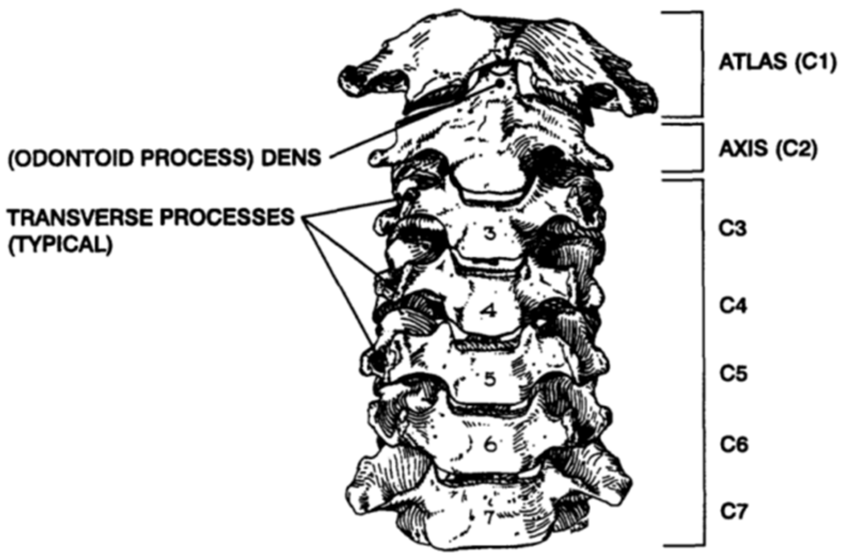


**Figure 2. Human Neck Anatomy (Grierson and Dunn)**

The majority of neck injury takes place in the upper neck when subject to combined axis loading (Cheng et al., 1982). Figure 3 displays bending, compression, tension and shear forces in the neck.  NHSTA studies that led to development of automotive neck injury criteria (The Nij; explained in a later section) deemed that the most significant neck injury mechanism in frontal impact (-Gx accelerative input) are axial loading (tension or compression) and front/back bending moment (flexion or extension).

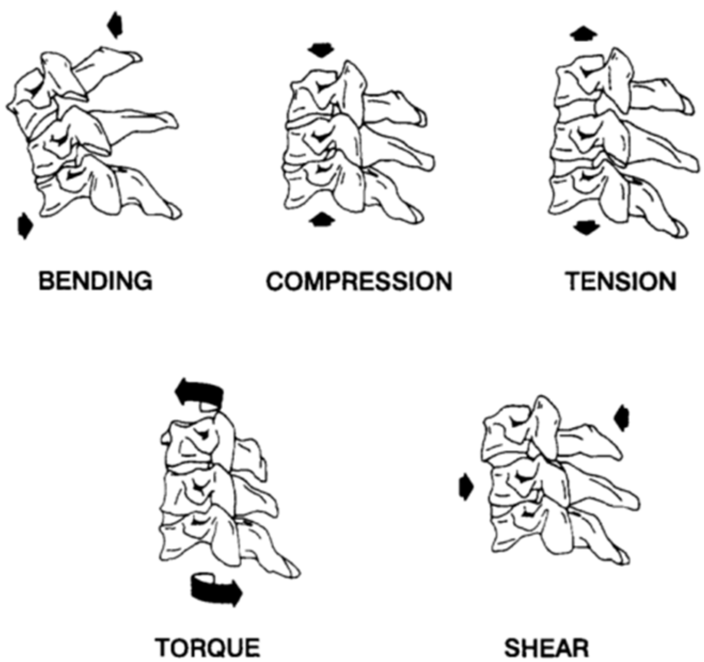


**Figure 3. Neck Loading Resultant Movements (Grierson and Dunn)**

Previous research indicates that a smaller neck is at a load bearing disadvantage compared to a larger neck due to the musculoskeletal composition of the neck and the scaling associated with neck circumference and vertebrae size (Salzar et al., 2009). Therefore, a larger neck is expected to be more effective at handling larger loads than smaller necks.  Injuries however, have been shown to vary between test subjects due to anthropometric factors like body weight, neck size and neck strength. Biofidelity agreement is further complicated when attempting to obtain human neck injury tolerance information. Indirect methods such as testing with human volunteers at low accelerations, cadaver testing at higher accelerations, computer simulation, and crash testing may be used to provide data that is similar to human response. However, this data may not be representative of human neck response when exposed to large accelerative input and should not indicate that ATDs can be a direct replacement in all ejection test scenario (Eppinger et al., 1999). Due to the previously explained restrictions that are inherent to testing with humans and the costs associated with PMHS testing; the Hybrid-III ATD with an instrumented neck has been made available in multiple sizes to account for anthropometric differences. Even though these steps have been taken to account for a majority of anthropometric differences, there have been studies that show the hybrid-III neck is not representative of the human neck, and some that show PMHS data could be skewed for the same reasons (Herbst et al., 1998). PMHS testing has also shown that incongruences exist between cadaver and human neck response. However, at present an ATD fitted with a Hybrid-III neck seems to be the best surrogate that can be used to evaluate neck response under accelerative loading, particularly during ejection system and helmet qualification testing.

**Injury Classification**

In 2008, the Association for Advancement of Automotive Medicine (AAM) met to finalize and classify injuries into a common scale that resulted in the creation of the Abbreviated Injury Scale (AIS). The AIS is an anatomically based, consensus derived, global severity scoring system that classifies each injury by body region according to its relative importance on a 6-point ordinal scale with the least sever injury labeled AIS 1 and the most severe labeled as an AIS 6 (AAM, 2008). In general AIS 1 is a minor injury, AIS 2 is a moderate injury, AIS 3 is a serious injury, AIS 4 is a severe injury, AIS 5 is a critical injury, and AIS 6 is a maximal injury (AAM, 2008). The AIS provides a means for scoping analysis effort as well as a concise way to present injury data to decision makers once it has been analyzed. Using a standard injury scale, gives the escape system and HMD developers, testers, and stakeholders a standardized injury definition to work from. The AIS also quantifies and provides a common understanding of injury level and how the injuries would affect the aircraft or vehicle operator. It has been proven useful to motor vehicle crash investigators when attempting to identify a mechanism of injury to aid in vehicle design. The USAF has applied the AIS in a similar manner as the motor vehicle industry. This research will utilize the AIS injury severity assessment scales.

The AIS classification is used to assess neck injury based on a universal scale. Quantifying the injuries by specific attributes allows a researcher to evaluate the forces that may lead to that specific level of injury. This classification is used as a guide for neck injury and is an integral part of risk function creation. The Air Force Life Cycle Management Center (AFLCMC) escape system oversight office has set the limit for future USAF escape systems at a 5% chance of AIS 2 or greater neck injury (White, J. E. Personal communication; May 2012).

In the field of injury biomechanics, difficulty lies in assessing AIS injury classifications when applying ATDs. Where injury is readily evident in human and PMHS testing via analysis after the accident or accelerative experiment, ATD "injury" is an elusive result. The advantage of ATD testing is evident when attempting to measure neck loads and when testing above safe levels for humans (Rash et al., 1998). One can only refer to the measured loads and the anticipated maximum allowable human loads to infer an injurious test condition.

AIS classifications are universally used for many industries, including the automotive, aviation, and medical fields. AIS categories are used to describe and assess injuries through a common medical terminology across the range of disciplines. For instance, PMHS are subjected to AIS injury inspection after being exposed to high levels of accelerative input to ascertain and codify any observed neck injuries.

The AIS levels that will be used as evaluation scenarios in this research are the AIS 2 and AIS 3 levels. AIS 2 injuries have a 1-2% probability of death associated with this classification injury and are coded as moderate, AIS 3 injuries are described as serious and have an 8-10 % probability of death associated with them (AAM, 2008). Based on retroactive analysis of ejection data in the USAF, 69% of injuries have been associated with injuries higher than AIS 3 (Grierson and Dunn, 1995). The following sections will highlight various neck injury criteria that are germane to ATD and human -Gx acceleration evaluation.

## Neck Injury Criteria

### Nij

Neck injury in the aviation community has become an area of interest since the incorporation of HMD technology. The advancement of HMDs has forced stakeholders to study the modes of injury in all 12 degrees of freedom. Formulated in the automotive industry, the Nij, can be related to aviation modes of injury. NHTSA has been studying the injurious conditions that are present in frontal vehicular impacts for decades and have a vast amount of data and test results available for review by the aviation industry. Ejection has distinct phases; catapult, windblast, wind drag/drogue chute deceleration, parachute opening shock and free fall. Much research has focused on the catapult phase where predominant resulting forces are compressive in nature. Not as much attention has been given to the other input forces experiences during ejection. Assuming the ejection seat does not rotate during ejection, wind drag and drogue chute ejection forces are equitable to frontal impact forces where flexion motions are created through a -Gx input. Tensile forces are presented in a less intuitive manner, as the body slows, the cranial inertia pulls it further away from the body, exacerbated by more extreme flexion.

The development of neck injury criteria within the automotive industry was initiated by the proliferation and ubiquitous incorporation of restraint systems and emphasis on crash testing (FMVSS No. 208). The automotive sector experienced a rise in death associated with operating vehicles that led to government regulations demanding that vehicles become safer. The incorporation of airbag technology led to the need for performance limits created for mid-sized male, small-sized occupants, and children, leading to emphasis on testing and injury prevention during frontal (-Gx) impact (Eppinger et al., 1999). It has been shown that there are similar modes of neck injury prevalent in automotive accidents and aircraft ejection (Nichols, 2007, Salzar et al., 2009). Similar to the automotive industry, the DoD fighter aircraft communities are interested in supporting aviator health through the design of safer escape systems capable of accommodating smaller, and larger individuals than are currently supported (Nichols, 2006). Reducing injury to the aircrew, viewed as the most important part of the weapon system, has surfaced as the primary issue to AF safety decision makers.

Neck injury criteria are defined for a number of different conditions such as injury mechanism, acceleration environment, and impact condition (Bass et al., 2006). The Mertz criteria were used in the automotive environment and are scalable to account for neck size (Mertz, 1993; Mertz et al., 1997; Armenia-Cope et al., 1993). Based on previous single and combined axis studies NHTSA researchers postulated that the two most critical modes of neck injury were axial force (tension or compression) and fore/aft bending (flexion or extension) (Cheng et al., 1982; FMVSS-208 200; Mertz and Patrick, 1971; Nusholtz et al., 2003; Eppinger et al., 1999). Associated critical values for each load (Fz and My) are used in the calculation of the Nij and are different based upon subject body mass. An Nij value below 1 limits risk of neck injury to a 22% risk of AIS 3 injury (Eppinger et al., 2000) As seen in Equation 2, the $F_{int}$ and $M_{int}$ values are the critical values established for the maximum tension (+Fz) / compression (-Fz) and flexion (+My) / extension (-My) (Eppinger et al., 1999; Mertz et al., 1978)

**Equation 2. NHTSA Nij Neck injury Criteria**

$$N_{ij} = \left|\frac{F_z}{F_{int}}\right| + \left|\frac{M_y}{M_{int}}\right|$$

The inadequacies of the Nij in escape system testing have been identified by Parr et al. (2013). New neck injury criterion developed by Parr et al., which will be called the MANIC(Gx) in this thesis to distinguish it from the Nij, has been compared to the Nij (Parr et al., 2013). The evaluation and comparison of Nij risk curves to MANIC (Gx) curves indicated that the Nij risk curves are inadequate for use in the aviation domain. The AFLCMC escape system oversight office has stated the desire for neck injury criteria that limit injury to a 5% risk of AIS 2 or greater (Parr et al.,2013). This is more conservative than the Nij limit of 1.0 used by NHTSA, which equates to a 22% risk of AIS 3 neck injury (Eppinger et al., 2000). A pilot may have to flee from capture upon landing while passenger vehicle accidents typically receive attention from emergency response crews, for this reason it is prudent to assign a more conservative injury criterion to the aircraft ejection environment.

### BEAM Criterion

The Beam Criterion (BC) was developed by Bass et al, and intended to be used in -Gx impact crash tests, specifically accounting for helmet mounted mass (Bass et al., 2006). The researchers used 36 head and neck complexes (portions of a full body cadaver) along with six whole cadavers. The head mounted mass was varied as well as the CG location. The cadavers were tested along with a set of matched THOR and Hybrid III ATDs. Injury and non-injury data points were pulled from these matched tests to produce risk functions and assign a BC value to a 50% injury intercept through survival analysis. Initially due to lack of BC critical values, the Nij 50$^{th}$ percentile Hybrid III ATD critical values were used. After risk function generation a second iteration was used to minimize the standard deviation of the 50% intercept and normalize the BC to a value of 1. To achieve the BC of 1, Fz and My value ratios were altered, shifting these ratios resulted in values that compared well with previous NHTSA intercept values. These risk functions ultimately resulted in the Beam Criterion creation.

The equation to determine the BC is similar to the Nij in structure and it initially attempted to account for multi-axis forces that are present in the C7/T1 intervertebral disc at the lower neck, including shear forces (Bass et al., 2006). The shear was determined to be a non-factor in this test scenario so it was removed. The researchers also postulated that the Nij criterion was not suitable for Hybrid III ATDs while supporting head supported weight, stating that the Hybrid III was not designed for testing under these circumstances. Bass concluded that THOR ATDs responded more similarly with the PMHS during sled tests. The upper neck flexion moment was also found to be lower than the lower neck response, due to the moment arm being exacerbated by additional helmet weight at the C7/T1 intersection.

**NIC**

Navy and Air Force researchers developed a comprehensive injury evaluation tool that incorporates upper and lower neck loading by combining 12 separate neck injury criteria (NIC) that were used in the aircraft escape community (Nichols, 2006). The NIC is intended to be applied to current and future HMD escape systems focusing on preventing injury. Nichols stated the inclusion of upper and lower neck loads was necessary as injuries have been known to occur at both locations during ejections. The NIC is comprised of six lower neck and six similar upper neck evaluation measures, they are: tension duration (+Fz), compression duration (-Fz), resultant shear duration (Fx, Fy), Nij (explained previously), maximum instantaneous lateral bending (Mx), and maximum instantaneous twisting (Mz). These six criteria provide data and limits for all 6 degrees of freedom in both the upper and lower neck response but they have been aggregated to be used as a "success criteria" not as an ejection safety pass fail indicator (Nichols, 2006). Instead a failure (exceedance of the limit) in one of the six areas listed previously is considered an indicator "flag" and that exceedance requires further evaluation by a subject matter expert (SME). Because of these facts, there is ambiguity built into the NIC criteria and its interpretation making it difficult to use as a system performance measure in developmental testing (Parr, 2014). There is a possibility of passing and failing a test in the same degree of freedom due to the way the duration and instantaneous load values are reported. A more in depth explanation, has been provided elsewhere (Parr, 2014). Multiple researchers have suggested that this tool is not valid for escape system level evaluation because of the inconsistencies stated here (Carter et al., 2000; Pellettiere et al., 2011; Pellettiere, 2012; Parr et al., 2014). This criteria has been shown to be most effective at predicting lower neck injuries in PMHS tests while the Nij under-predicted and the BC over-predicted observed injury during tensile force testing (Salzar et al., 2009).

**Tensile Neck Injury Criterion**

Neck injury criteria were originally developed for automotive frontal impact testing that indicated the most common mode of injury was frontal flexion. Tension not flexion is the primary loading mechanism in aviation and Carter investigated the development of alternate evaluation criteria (Carter et al., 2000). The two phases of ejection where tensile forces are most significant are during wind blast and parachute opening shock (Parr, 2014). This study used a combined human/PMHS data set to develop risk curves using logistic regression that were body size specific. These risks curves show that a tensile load of 2320 N for a large subject and 1740 N for a small subject indicate a 5% probability of AIS level 3+, this finding is validated by other studies (Carter et al., 2000). Carter et al. highlight the limitation of their single-axis injury criterion when applied to ejection environments with multi-axial input. Parr et al. (2013) provided an update to the Carter et al. tensile criterion by including additional PMHS data into the analysis and generating risk functions using survival analysis. The researchers' future research recommendations focus on incorporating multi-axial components for improvement of the Tensile Neck Injury Criteria. The following section summarizes these improvement efforts and culminates in the Multi-Axial Neck Injury Criteria (MANIC) intended for use as the USAF testing standard.

### MANIC

The MANIC is an improved neck injury criteria developed by Parr (2014) based upon previous research performed by Perry and others (Perry et al., 1997). The previous research highlighted the need for development of multi-axial, pilot-scale neck injury criteria that could be used to assess new and legacy escape systems with incorporated HMDs. In an effort to meet the USAF escape system oversight office's requirement for neck injury, a multi-axis neck injury criterion, the MANIC, was developed. The initial formulation of this criterion is shown in Equation 3.

**Equation 3. Multi-Axial Neck Injury Criterion (MANIC) (Parr, 2014)**

$$MANIC = \sqrt{\left(\frac{F_x}{F_{xcrit}}\right)^2 + \left(\frac{F_y}{F_{ycrit}}\right)^2 + \left(\frac{F_z}{F_{zcrit}}\right)^2 + \left(\frac{M_x}{M_{xcrit}}\right)^2 + \left(\frac{M_y}{M_{ycrit}}\right)^2 + \left(\frac{M_z}{M_{zcrit}}\right)^2}$$

Force components and bending moment components are compiled in a root sum of squares format using force and moment data that has been recorded during single axis tests to create risk curves and evaluate for injury in each specific input axis; resulting in a MANIC(Gx), MANIC(Gy) , and a MANIC(Gz). These combined values can be looked at as a single evaluation criterion, and based upon developmental test results a pass or fail determination can be made since the risk functions will provide injury risk and classification information. MANIC data components were missing in some of the three acceleration planes due to a lack of data in the literature. The logic behind these shortcomings is listed in the research. For more about the missing components or the creation of this criteria refer to the original research (Parr, 2014). The resultant Gx, Gy, and Gz equations are shown below in Table 1 along with the applicable limits.

**Table 1. MANIC Components (Gx, Gy, Gz) and limits (Parr, 2014)**

| Criteria Element | Limit |
|---|---|
| $MANIC(-Gx) = \left\lvert \frac{F_Z}{F_{Zcrit}} \right\rvert + \left\lvert \frac{M_Y}{M_{Ycrit}} \right\rvert$ | **Peak MANIC(-Gx) < 0.56**<br>Less than 5% Risk of AIS 2+ Injury<br>**(<0.72 for AIS 3+)** |
| $MANIC(Gy) = \sqrt{\left(\frac{F_X}{F_{Xcrit}}\right)^2 + \left(\frac{F_Y}{F_{Ycrit}}\right)^2 + \left(\frac{F_Z}{F_{Zcrit}}\right)^2 + \left(\frac{M_Y}{M_{Ycrit}}\right)^2 + \left(\frac{M_Z}{M_{Zcrit}}\right)^2}$ | **Peak MANIC(Gy) < 0.48**<br>Less than 5% Risk of AIS 2+ Injury<br>**(<0.53 for AIS 3+)** |
| $MANIC(-Gz) = +Fz$ | **Peak MANIC(-Gz) < 922 N/207 lb**<br>Less than 5% Risk of AIS 2+ Injury<br>**(<1136 N/256 lb for AIS 3+)** |

Ultimately, the missing data did not affect the ability for risk curve creation, which is the core of neck injury risk prediction and the most usable tool for decision makers. The MANIC injury criteria can be used to generate a set of three human-based risk functions in each input acceleration plane Gx, Gy and Gz. Specific AIS level risk functions can be created by using the recorded human and PMHS neck response, for MANIC research AIS level 2 or greater (AIS 2+) and 3 or greater (3+) risk curves were created for comparison and evaluation. A 5% injury probability limit can be applied when using the MANIC risk curves, instead of the 22% for the Nij (Parr, et al., 2013). Each of the three specific input conditions produces varying amounts of head and neck movement during testing. These neck movements are the result of kinematic response, bracing, muscular contraction (human only), test setup, and subject positioning. The first application of this criterion was a test case completed by Parr in 2013 in the -Gx acceleration axis, comparing the differences between NHTSA and MANIC(Gx) human risk curves, some of these comparisons are shown in Figure 4, Figure 5, and Figure 6.

The MANIC risk curves use survival analysis (SA) methods that have been applied to the field of injury biomechanics environments in previous research (Hosmer et al., 2008; Cutcliffe et al.,2012; Bass et al., 2006). SA uses human sub-injurious data combined with an injurious PMHS data set creating a dichotomous data set for SA evaluation. This method requires noting the AIS level associated with the injury points to form a risk curve similar to the one shown in Figure 6. Parr applied human study data as well as PMHS and ATD data to each axis of acceleration to develop three separate risk curves (Parr, 2014). With the human subjects experiencing non-injurious 6-10 G accelerations and the PMHS and ATD subjects experiencing 8-45 G's, four of these resulting in injury (four of the six PMHS). The point of injury for the PMHS were not known until post test examination, zero human injury (AIS2+) were noted, creating a dual (right and left) censored data set. SA is capable of accounting for left and right censored data and is more applicable in this domain than logistic regression methods which made it the appropriate tool for Parr's research.

The MANIC provides a means to evaluate the neck response during all four ejection phases. It defines injury risk using specific experimental force input data, or a combination of forces, resulting in a definitive injury prediction (Parr, 2014).

**Table 2. MANIC Risk Function Input Matrix (Parr, 2014)**

| Laboratory Input Acceleration | Human/PMHS Neck Response | | Risk Function | User Defined Limits | |
|---|---|---|---|---|---|
| Gx | Fx,Fy,Fz,Mx,My,Mz | AIS Values | MANIC(Gx) | $P$ (inj) X | |
| Gy | Fx,Fy,Fz,Mx,My,Mz | AIS Values | MANIC(Gy) | $P$ (inj) Y | MANIC |
| Gz | Fx,Fy,Fz,Mx,My,Mz | AIS Values | MANIC(Gz) | $P$ (inj) Z | |

The use of the complete MANIC criterion will not be applied to this research but the Gx portion (MANIC(Gx)) shown in Table 2 will be utilized, concentrating on ATD to human neck response relationships. Based upon the aforementioned literature; aviation specific MANIC(Gx) limits that have been identified (<5% P(AIS 2)) and will be utilized for the remainder of the research. The methods and implementations of these approaches will be discussed in Chapters III and IV.

The figures below show a graphical depiction of the differences in injury probability between MANIC(Gx) and Nij (Figure 4 , 5 and 6). Similar construction characteristics and the common use of tensile and flexion limits allow for direct comparison between the two.

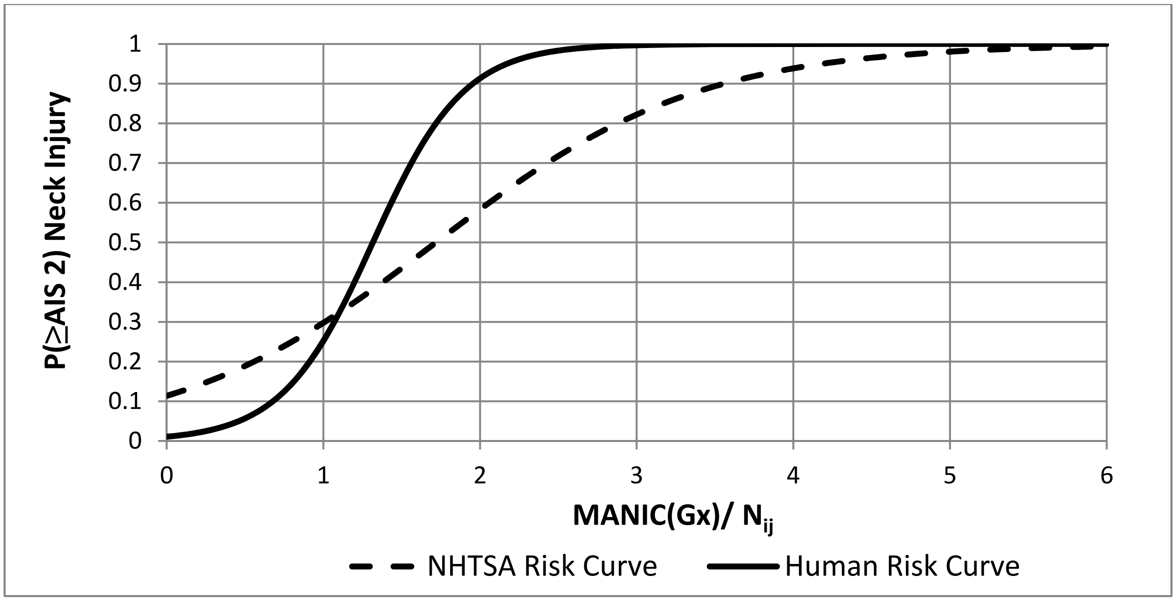


**Figure 4. Probability of AIS 2 or Greater NHTSA and Human Neck Injury Risk Curves (Parr et al., 2013)**

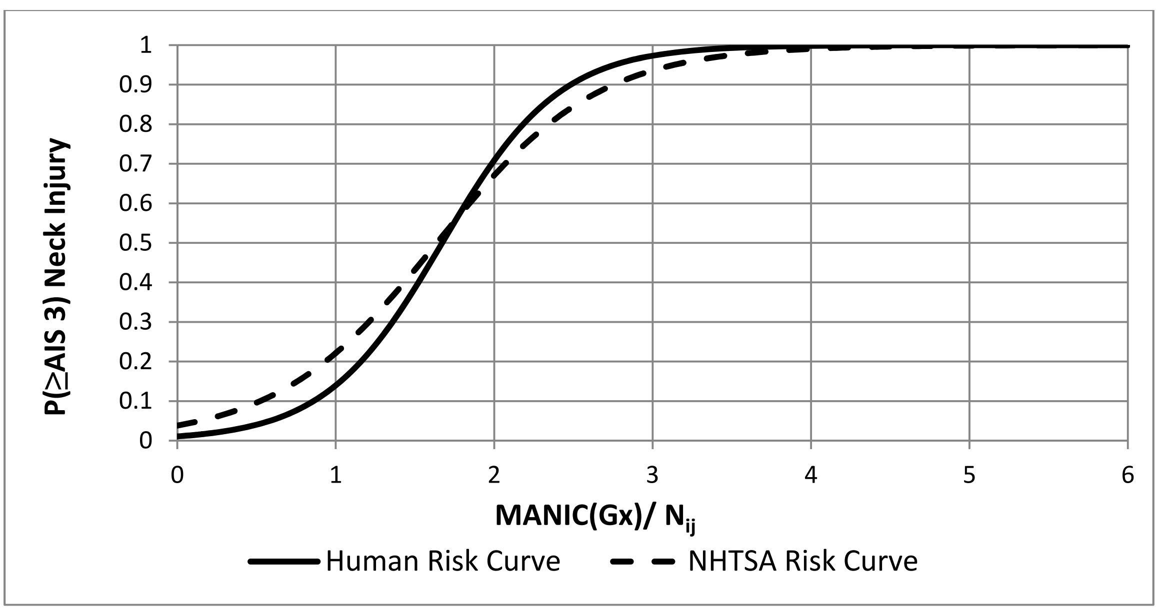


**Figure 5. Probability of AIS 3 or Greater NHTSA and Human Neck Injury Risk (Parr et al., 2013)**

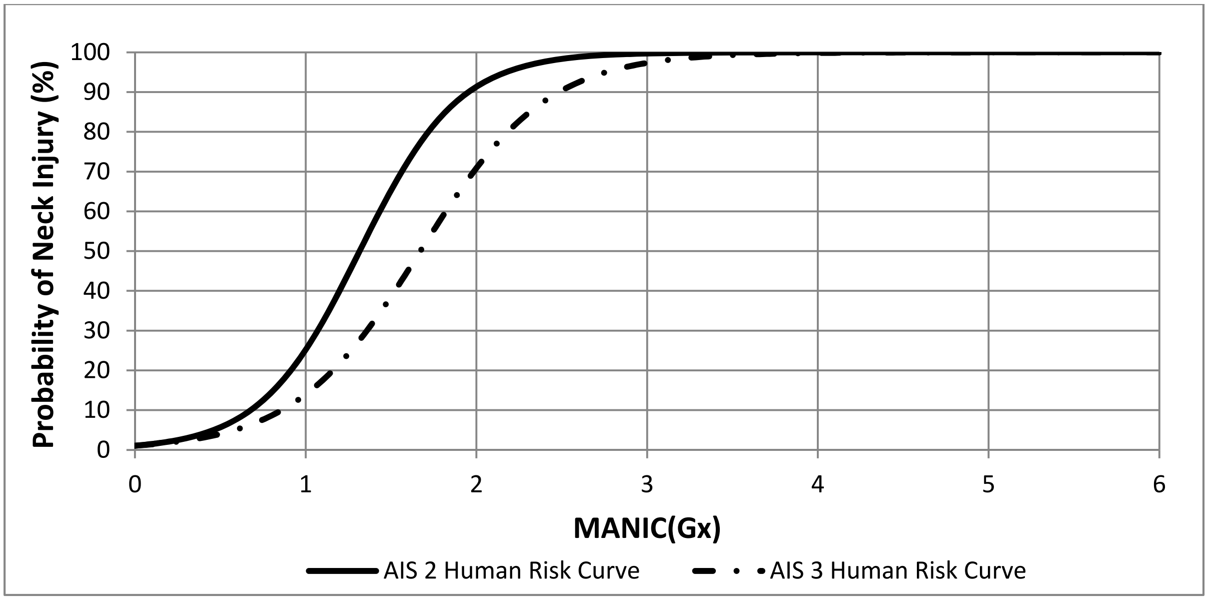


**Figure 6. Human AIS 2+ and AIS 3+ Risk Curves (Parr et al., 2013)**

## Statistical Methods

Statistical evaluation is a very important component of any research that is focused on expanding the existent research base. The evaluation of neck injury during ejection requires sound quantitative statistics, ensuring that the results will hold up under scrutiny. Linear regression is a practice that is most commonly applied to how two variables relate by fitting a linear equation to observed data. Human and ATD linear models will be useful in this research. In Chapter III and IV it will be used to characterize a human to ATD transfer function method.

## Summary

In summary, no single neck injury criterion has emerged for use as an injury predictor during ejection, with or without head supported mass. Human kinematics have only been observed and documented at low levels, this data is a limiting factor when attempting to predict injury in a highly dynamic high-G environment. Neck biomechanics are complicated and have myriad of input factors potentially affecting human neck response during ejection. ATDs and PMHS provide a surrogate to evaluate, however, the internal reactions of human musculature, tendons and joints are difficult to emulate via ATD and PMHS experiments. Human testing with the same subject and input conditions have been known to be highly variable; removing this variability with an ATD is a task that lies outside of this research scope. Continued research in ejection kinematics is required in order to build a more accurate surrogate for ejection testing (Salzar et al., 2009).

Some of the areas that have not been agreed upon are related to applying the data, ATD bio-fidelity, testing equipment and methodology misrepresentations. Many research entities have postulated dissimilar injury evaluation criteria. Without a common language, it has proven difficult for future researchers to communicate, which has complicated the verification of existing results. Speaking in the same vernacular will allow the transfer of ideas between industries and stakeholders, as well as reducing the amount of rework associated with confirmation of previously defined concepts. The future efforts to integrate these results and clearly define a single method of predicting neck injury associated with ejections are the most challenging aspect of this field of study. Evaluating existing data and developing an ATD-to-human transfer function is at the heart of this research and will be expounded upon in the next few chapters.

# III. Comparison of Human and ATD Neck Response to Frontal Impact (-Gx) Acceleration

## Chapter Overview

The following paper entitled "Comparison of Human and ATD Neck Response to Frontal Impact (-Gx) Acceleration" has been accepted for presentation at the 2016 Industrial and Systems Engineering Research Conference. It describes the creation of a proposed transfer function between ATD and human neck response through the use of linear regression modeling. A short example application is also included. The paper is presented as it was submitted without removing or editing content.


## Abstract

Helmet Mounted Display (HMD) technology has become commonplace in many military applications. The current research proposes a method to create a transfer function to enable the direct application of a previously developed human-based neck injury metric called the MANIC(Gx) to accelerative tests performed with anthropometric test device (ATDs) during prototype and developmental testing in the systems engineering process [1]. Data was collected from previous accelerative sled experiments where ATDs and human/post mortem human subjects (PMHS) were accelerated over a range of frontal (-Gx) loading and peak MANIC(Gx) was calculated. Linear regression was performed for each data set and the difference between human and ATD expected value for peak MANIC(Gx) was analyzed. It was observed that ATD MANIC(Gx) expected values were lower than the human values at each level of input acceleration above 2 G. A human to

ATD transfer function method is proposed based on these observed differences. This transfer function could make the previously developed human-centric neck injury criterion directly applicable to developmental safety testing with ATDs [1].

**Introduction**

The proliferation of helmet-mounted displays has led to increased head supported mass in military fixed wing and rotary wing aircraft systems. This increased head supported mass has in-turn increased the risk of neck injury. More specifically, the need for pilots to support additional weight on their heads can lead to acute neck injuries from instantaneous accelerative forces that occur during ejections or other crash-related events. With the ubiquitous integration of HMDs and other head mounted equipment (e.g. night vision devices and helmet mounted cuing systems) into the military operational environment, a significant amount of consideration has been given to aviation specific neck injury criteria. However, current methods do not permit design engineers to accurately predict how new HMDs will affect the neck of the user in the dynamic and unpredictable aviation environment.

A United States Air Force (USAF) policy was previously issued that expands the acceptable size and weight range of future aircrew, causing special concern for the safety of aircrew at the smaller end of the spectrum. The additional injury likelihood for pilots weighing less than 136 lbs. has forced the F-35 Joint Program Office to restrict the use of this platform to pilots weighing at least 136 lbs. (USAF Public Affairs Office, 2015).

Integration of new technology often poses problems for end users if not implemented correctly and with the user in mind. Cost is often times the main concern when a new piece of hardware is available for operational use. In a business environment, the added value and or utility are easy to discern; the costs of integration, training and hardware are always under evaluation, providing shareholder value is the primary concern. In these environments, a business case approach is commonly taken to make a cogent decision about the benefits gained (or lost) by integrating the new hardware, and a decision is made to invest in the new capability or to focus resources elsewhere.

In the Department of Defense (DoD), where profit is not a measurable concern, and where numerous stakeholders influence investment priorities, many challenges are present when facing advanced technology integration decisions. A Decision Maker (DM) in the DoD must be vet the decision with respect to likely future needs, considering both short term acquisition costs as well as longer term operations, maintenance, and disposal costs.

Integration of Helmet Mounted Display (HMD) technology is considered a crucial part of the future landscape of operations inside (and outside) the DoD [3]. Whether ground-based, or in the air, the user is forced to accommodate the additional head supported weight of any HMD hardware, while performing their mission. The benefit of potential operational advantages should offset the costs of potentially altered duty performance and increased safety risk from supporting the additional weight. The current research focuses particularly on the increased risk of injury due to increases in head supported weight, although it is recognized that chronic stress injuries and fatigue are also of concern. Specifically, this research seeks to create a transfer function between human and ATD response to $-G_x$ accelerative input, enabling the direct application of a previously developed human neck injury criterion (with a comparable structure to the Nij) to accelerative tests performed with ATDs to ultimately steer future helmets towards a safer, more functional design [1]. Development of HMDs must account for the downstream effect that the increased hardware and resulting increased head supported mass will have on the user. If these effects of new hardware hinder performance *and* add increase neck risk during ejection, a negative cost to benefit ratio is created. The cost to benefit ratio of new technology must be thoroughly scrutinized before these systems are integrated into legacy systems or incorporated into new development efforts. This scrutiny must consider the likelihood of human injury as an important aspect when quantifying costs and operational advantage as benefits.

To capture the risk, first the relationship of ATD and human biomechanics must be quantified. This study focuses on the ATD to Human relationship in the -Gx direction only. Multiple cadaver and ATD automotive crash tests have shown that the critical forces present in a neck during -Gx loadings are tension (+Fz) and bending moment (My) [4, 5]. These findings have propelled the aviation community to develop an aviation specific neck injury criteria that can be utilized to translate the neck responses observed in ATDs to humans. This neck injury criterion was developed by Parr et al. and has a similar structure to the Nij formulation but has different risk functions than the Nij, thus it is a distinctly different neck injury criterion from the Nij [1]. For this reason, hereafter it will be referred to as MANIC(Gx), where MANIC stands for multi-axial neck injury criterion.

This paper seeks to answer the following research question:  what is the difference in peak MANIC(Gx) between human/PMHS and ATDs over the range of -Gx accelerative input observed from previous laboratory experiments?  An additional question to be answered is: can the observed differences in peak MANIC(Gx) be used as a transfer function to make the Parr et al. human-based neck injury criterion  more appropriate for use in testing with ATDs?

**Background**

The Air Force Life Cycle Management Center (AFLCMC) has requested the development of a multi-axial criterion for evaluating pilot safety during ejection. The current evaluation techniques do not provide a stand-alone solution for this problem. Developing the state of the art neck injury criteria has proven to be an iterative process. This new evaluation criteria is to be used in future injury prediction calculations at the program level during prototyping and developmental testing [1].

The automotive industry created the basis of the neck injury criterion that has been used in aviation applications.  The National Highway Traffic Safety Administrations (NHTSA) has been studying the injurious conditions that are present in frontal vehicular impacts for decades; and have a vast amount of data and test results available for review and application to ejection.  There are similar modes of neck injury prevalent in automotive accidents and aircraft ejection [6, 7].  Decomposing the phases of ejection into singular force vectors allows a comparison between ejection modes of injury and automotive crash tests. Ejection has distinct phases: catapult, windblast, drogue-chute deployment, main-chute deployment and seat-man separation,, and free fall.

Windblast, drogue-chute deployment, and main-chute deployment can create a -Gx acceleration on a pilot that is very similar to crashing an automobile [1]. NHTSA developed the Nij in an effort to accurately assess the human neck response during a frontal impact to evaluate new car airbag safety [4]. After multiple test were completed and examined, it was determined that human neck injury was most likely to occur as a result of +Fz (tension) and +My (flexion) forces which occurred during such a frontal collision [4]. A specific formula and intercept values ($F_{int}$ and $M_{int}$) were also developed to provide a single metric, referred to as $N_{ij}$, which could be applied across multiple passenger weight ranges [4]. For complete details on the Nij, the reader is referred to publications by Eppinger et al. [4, 5]. However, the Nij formulation is shown in Equation 2. NHTSA Nij Neck injury Criteria

$$N_{ij} = \left|\frac{F_z}{F_{int}}\right| + \left|\frac{M_y}{M_{int}}\right| \qquad (1)$$

However, this formula alone does not provide information regarding the likelihood or severity of human injury during an impact. Injury severity is captured through the use of the Automated Injury Scale (AIS). This scale provides researchers a consistent method for classifying each injury according to its severity on a 6-point ordinal scale, with the least severe injury labeled AIS 1 and the most severe labeled AIS 6 [8]. The AIS provides a means for scoping analysis effort as well as a precise way to present injury data to decision makers once it has been analyzed. Limiting ejection injuries to below AIS 2 or AIS 3 levels is common in USAF risk analysis; therefore these levels are commonly used during neck injury risk analysis. Years of extensive NHTSA research with the Nij has resulted in a set of risk functions generated with logistic regression that predict probability of injury (AIS 2 through 6) based upon an observed Nij value (Eppinger et al., 1999; Eppinger et al., 2000).

The USAF has previously used a notional guide for design, development, and acquisition of HMDs called the Knox Box. The Knox Box, developed by USAF ejection researchers was an effort to provide guidance to US Air Force Research Laboratory and USAF acquisition program personnel who were developing HMD prototype designs [9]. The Knox Box uses mass and CG as its main metrics for design constraints, creating a virtual box that all HMD prototype designs should fall within. The goal was to limit the weight and off-axis moment (CG) to minimize chances of pilot neck injury during catapult phase of ejection. This criterion was developed as an early design guideline, not intended for long-term use in HMD designs however; it is still being utilized as the starting point for HMD design [9].

The US Navy and Air Force have developed a 12-part Neck Injury Criterion (NIC) based on automotive injury criteria. The NIC uses instrumented aerospace ATDs of varying sizes configured with a Hybrid III neck. Those ATDs were subjected to sled test ejections at differing equivalent airspeeds to permit the quantification of likely head accelerations and neck forces which a pilot might encounter during an ejection while wearing a prescribed helmet and when ejecting with a specific ejection system design [6]. The NIC is currently the requirements generation tool of choice in HMD and ejection seat development for DoD fixed wing aircraft. Although the NIC is currently being used by the F-35 program for ejection evaluation testing, past research has highlighted some limitations of the NIC [1]. One of the most significant concerns is inconsistent limits for the various neck loads included in the 12-part criteria. This criteria includes some elements that are not linked to specific AIS injury levels nor supported by underlying injury risk curves to allow quantification of the risk percentages associated with a specific level of observed loading [10]. The use of the Hybrid III neck in these evaluations is noteworthy as this mechanical structure has been designed to respond similar to the human neck during accelerative events, however, some research has indicated that its response is not always consistent with the response of the human neck (ref).

Attempts have been made to account for the discrepancies in the above methods and to fulfill the requirements set forth by AFLCMC. One proposed method, the Multi-Axial Neck Injury Criteria (MANIC), was designed to include as many of the six major forces that could be observed in the upper neck as a result of accelerative loading as necessary [1]. The MANIC is the only proposed neck injury evaluation tool that fulfills all of the requirements that have been specified by the Air Force Life Cycle Management Center for a neck injury criteria. However, the MANIC provides human risk curves for each primary axis of acceleration (Gx, Gy, and Gz) constructed using a combination of data from accelerative tests with human and post-mortem human subjects (PMHS) and application of these human risk functions can only be applied during ejection tests using ATDs if it is assumed the ATD and the mechanical neck in the ATD respond equivalent to a human pilot, an assumption the literature has already demonstrated is flawed [1,6,7] Therefore this research will seek to create a modified MANIC(Gx) metric, which is applicable to future qualification tests conducted with ATDs employing the Hybrid III neck.

## Methods

Test data used for this analysis was collected from the USAF Biodynamics databank (BIODYN), a part of the Collaborative Biomechanics Data Network (CBDN) that is operated and maintained by the Human Effectiveness Directorate (RH) under the 711$^{th}$ Human Performance Wing at Wright-Patterson AFB, OH. All corresponding tests were conducted on the Horizontal Impulse Accelerator (HIA) located in RH at Wright-Patterson AFB. The acceleration profile was a half-sine pulse with 65ms of rise time and 150ms duration for both human subject and ATD testing. The goal of the methods described here were to gather adequate ATD and human data to produce a statistically significant linear regression (LR) for each group.

### Apparatus:

All ATD tests were accomplished using the HIA test sled. The sled was used to accelerate the subjects in the -Gx axis. Two of the three high-G (above 10G) HIA tests used the “40G” seat fixture with seat pan and seat back angle of 30° (seat reclined 30°) in the x-axis. The third ATD test used a seat that was not reclined at all (90°). All ATDs wore the HGU-55/P flight helmet (Buhrman, 1996). The low G ATD and human testing and comparative PMHS test data collection was accomplished via a similar test setup. Seat angles can affect the forces experienced by the neck during-Gx acceleration, for this analysis the data was limited and it has been assumed that the different apparatus setups will yield similar neck response. For a complete description of the human and PMHS testing, refer to the original literature for specific setup information [10,11].

**ATD data:**

All data selected and utilized for the efforts of this research consisted of ATDs that were subjected to a -Gx input accelerations from 6 to 45 G's. Two types of ATDs were utilized in the tests, the Advanced Dynamic Anthropomorphic Manikin (ADAM) and the Joint Primary Aircraft Training System (JPATS). Both of these ATDs were used to collect data for this research through an instrumented Hybrid III neck. The weight ranges for all ATDs that were used in the scope of this research were from 116-245 lb. The 116 lb. ATD is representative of the lower range of USAF pilots. The 245 lb. ATD was used to represent the larger pilot. The tests were purposefully selected to show multiple ATD types accelerated at various input levels for completeness.

**Human and PMHS Data:**

The human data used in this study was the data used in the research conducted by Parr [10]. This data consisted of non-injurious data points at -Gx accelerations between 6 and 10 G's. The Human subject's weight ranged from 119-276 lbs. A limited number of human data points (67) were collected due to the cost and time required to test humans. The human subjects were fitted with a bite bar and instrumented helmet apparatus for data recording purposes. Acceleration data from the accelerometers on the bite bar were converted into tension (Fz) and flexion (My) forces for use in the MANIC(Gx) calculations according to methods outlined by Parr et al. [1]. Additionally, data from experiments with 6 PMHS was used to attain high G data similar to the ATD. The PMHS weight ranged from 110-211 lbs. and the test sled input (-Gx) accelerations ranged from 32-39G with an observed peak MANIC(Gx) value of 3.802 [1]. The PMHS data collection and MANIC(Gx) calculation specifics are available in the research of Cheng et al. [11] and Parr et al [1]. These two data sets were combined and a linear regression was performed, with human data representing neck response below 10 G's and the PMHS data representing neck forces experienced when accelerated above 10 G's. The compiled data regression output will be referred to as the "human" line.

**Neck Criteria Calculation:**

The MANIC(Gx) was calculated using raw neck force data from the load cells in the neck of each ATD and the appropriate human neck force calculations (described by Parr et al) [1]. The data was used to calculate the peak MANIC(Gx) observed over the entire test, using the MANIC(Gx) formula from Equation 1. Caution was taken to use only the initial neck pulse movement data, and censor out the secondary neck movements, so as to not provide a faulty peak MANIC(Gx). The intercept values in Table 3 were used based on ATD weight.

**Table 3. MANIC(GX) ATD Critical values**

| | Small ATD: 96-135 lbs. | Mid-Size ATD: 136-199 lbs. | Large ATD: 200-245+ lbs. |
|---|---|---|---|
| Tension (lb.) (+$F_z$) | 964 | 1530 | 1847 |
| Compression (lb.) (-$F_z$) | 872 | 1385 | 1673 |
| Flexion (in-lb.) (+$M_y$) | 1372 | 2744 | 3673 |
| Extension (in-lb.) (-$M_y$) | 593 | 1195 | 1584 |

**Linear Regression:**

JMP Version 12 statistical software was used to analyze the data (SAS, 2015). Linear regression of peak MANIC(Gx) versus accelerative input (G) was performed on the human and ATD data to create two separate lines. The first regression line was created using the data that varied from 116-245 lb. ATDs. The next regression line was built by using the existing "human" data comprised of both human and PMHS data sets. The peak MANIC(Gx) data points were plotted against their respective accelerative input. After JMP analysis, the regression line expected value equation for human and ATD was plotted on the same chart for comparative purposes. Regression through the origin (RTO) was used for the human data since it can be reasonably assumed that when accelerations (independent variable) are not present, the MANIC(Gx) value (dependent variable) will be zero. The ATD data were already representative of this assumption and were plotted without RTO formatting. The RTO approach induces some limitation in the statistical analysis by making the $R^2$ value unusable. It also should be noted that any interpretation of the regression line that falls outside the observed data points should be avoided.

## Results and Discussion

When comparing the ATD LR to the human LR at similar loading conditions, the two respond quite similarly across the entire range as would be expected. However, the expected human MANIC(Gx) value is increasingly greater than that of the human from 2-45 G, refer to Table 4 for the LR model source equations. The regression model for humans was significant at a p-value of less than .0001 and for ATDs at a p-value of less than .0001.

**Table 4. ATD and Human MANIC(Gx) Linear Regression Model Equations**

| Subject | Equation |
|---|---|
| Human/PMHS | MANIC(Gx) = 0.0400669*G |
| ATD | MANIC(Gx) = 0.0177993*G+0.0438443 |

It is noteworthy that the original data set did not have representative tests below 6G. Acceleration levels less than 6 G are generally safe operating conditions for pilots, indicating that the differences in the LR lines below 6G are not as critical as the higher accelerations. The most significant discrepancies in the levels of observed MANIC(Gx) occur at high accelerations, shown in Figure 7. Linear Regression of ATD and Human MANIC(Gx) Data

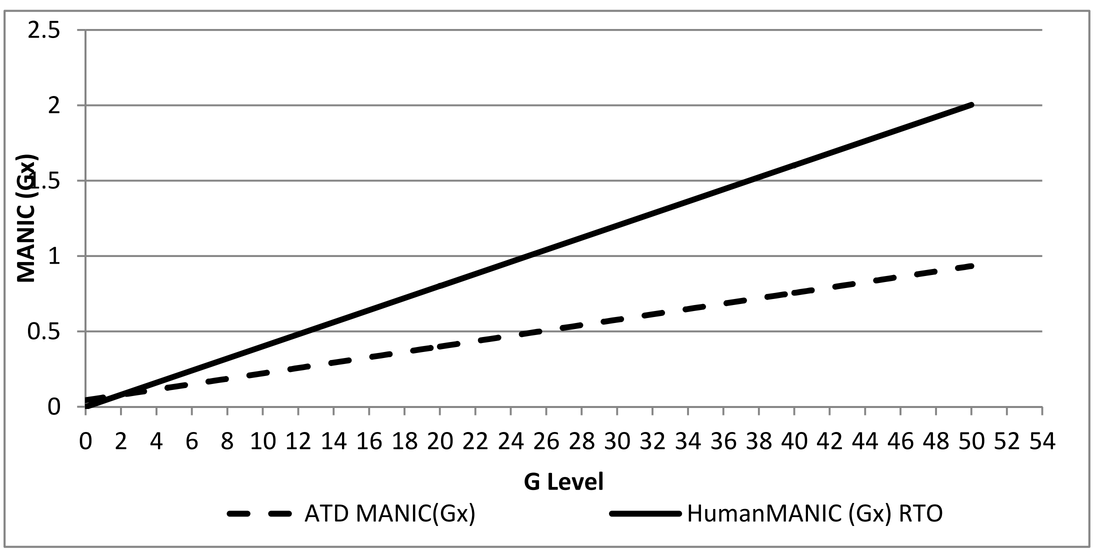


**Figure 7. Linear Regression of ATD and Human MANIC(Gx) Data**

It should also be noted that during ejections, it is unlikely that the pilot would experience -Gx impact levels above the indicated -Gx levels. PMHS testing began at 32 G, leaving a significant gap in the human response values between 8 G and 32 G. The gap that was created forced the JMP software to fit a line between two disparate data sets that exhibited dissimilar variance, the results can be seen in Figure 8 and Figure 9. Presumably, when performing linear regression, the data has similar variance for comparison. In this case that was not possible, due to the limited amount of –Gx PMHS data that was available (N=6). Additionally, PMHS tests do not have a mechanism to indicate when injury took place, leaving the PMHS data left centered. The human line therefore could be significantly improved with additional data. Higher confidence can be placed in the ATD results however, even though some of the MANIC(Gx) levels occurring at high G were lower than expected and caused some concern. These ATD linear regression results may need to be verified through additional testing or a similar analysis of existing data. The peak expected value from the MANIC(Gx) at 39G for ATDs is 0.74 and for the humans it is 1.56. This difference is the largest at the 39G point and measures a 0.82 MANIC(Gx) difference. Accelerations in the -Gx direction were used here to compare the load of ATDs and humans by linear regression analysis.

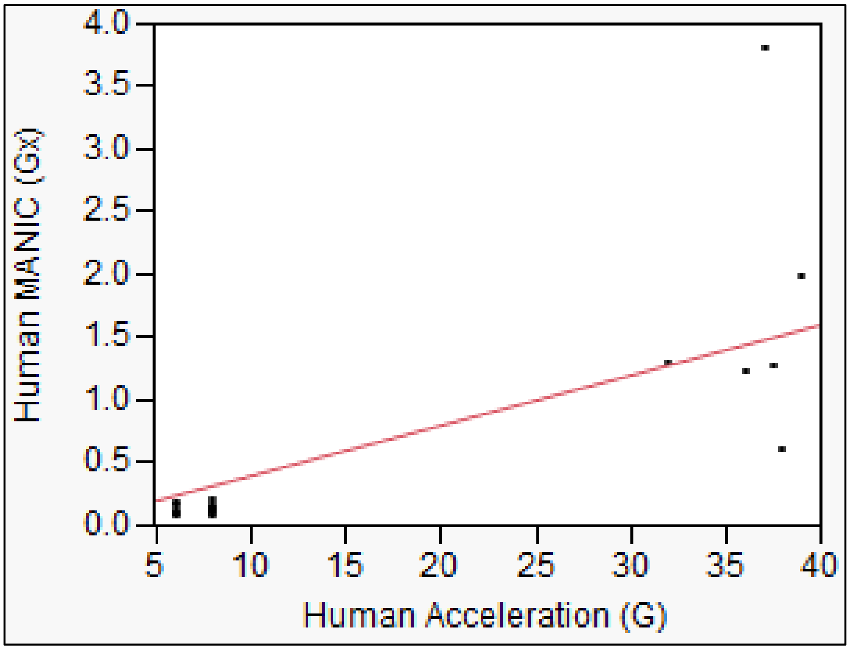


**Figure 8. Human Linear Regression Data Plot with Regression through the Origin**

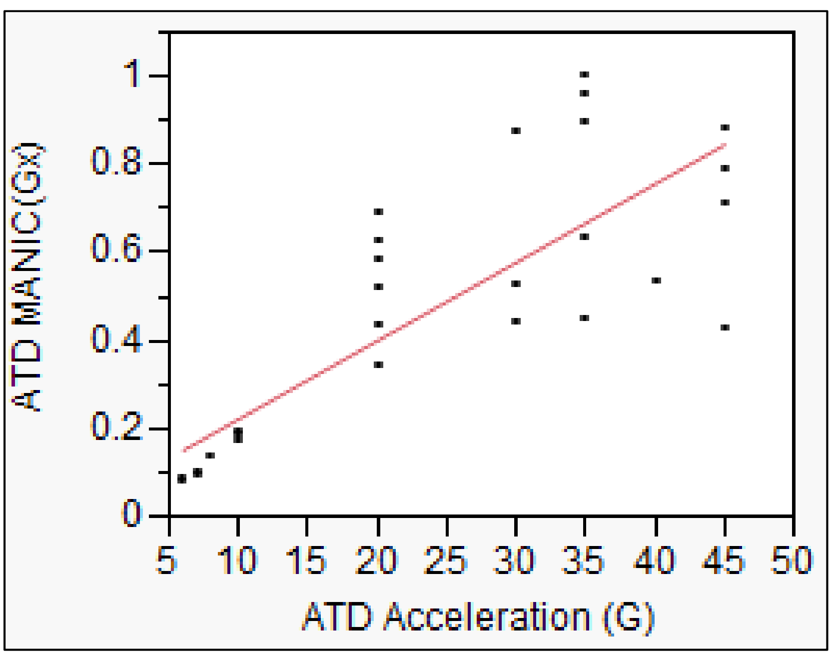


**Figure 9. ATD Linear Regression Data Plot**

The goal of this study was to understand and quantify the difference between human and ATD MANIC(Gx) over the range of -Gx accelerative input that could be experienced by a pilot during ejection. The human expected MANIC(Gx) values are greater than the ATD MANIC(Gx) expected values as the G-levels increase. This quantified difference between the expected MANIC(Gx) of a human and an ATD could be used in follow-on research when testing with ATDs. An ATD MANIC(Gx) value could be translated to a human value by taking the difference in expected MANIC(Gx) values at the specific G level of the observed test. This ATD-transformed value could then be evaluated using previously developed human MANIC(Gx) risk functions to determine the probability of injury for that test. For example, take a single ATD MANIC(Gx) value from a hypothetical data set where MANIC(Gx) was recorded to be 0.3197 at 15.5 G's. The equivalent human MANIC(Gx) expected value, based on a calculated G specific transform, would be 0.621. Thus ATD transformed values could be evaluated using the previously developed human risk functions. In future research this transfer function method could make the previously developed human-centric neck injury criterion directly applicable to ATD developmental and safety testing of USAF escape systems incorporating HMDs [1].

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# IV. Development of a Frontal Impact (-Gx) Neck Injury Criterion

## Chapter Overview

The following chapter is comprised of an article that was prepared for submission to the Aerospace Medicine and Human Performance journal. The article is intended to shed light on the relationship between ATD and human neck response to frontal impact (-Gx) and the suitability of human risk functions for use in conjunction with ATD system level testing for use as human injury predictors. The article has been formatted to be integrated into this thesis document and is expected to be updated for submission to the journal.

## Abstract

**BACKGROUND:** The use of Helmet Mounted Displays is becoming ubiquitous in the field of aviation, adding to pilot head-supported weight and increasing the risk of neck injury during ejection. Developing neck injury criteria to evaluate and quantify neck injury risk is important to ensure ejection systems are produced within acceptable safety standards. **METHODS:** An ATD to human transfer function for is developed that quantifies the difference between Anthropomorphic Test Device (ATD) and human neck response data from -Gx accelerative tests, and demonstrates how this transfer function can be applied to ATD test data to make previously developed human risk functions directly applicable to interpreting the ATD data with a human-based neck injury criterion. To gain an understanding of how the MANIC(Gx) can be applied to escape system testing, the ATD test values were evaluated using the current state of the art MANIC(Gx) human risk curves (AIS specific). **RESULTS:** A difference between the human and ATD MANIC(Gx) neck response was measurable, the ATD indicated lower MANIC(Gx) levels at equivalent AIS risk probabilities. For instance, at 5% probability of neck injury risk, the ATD MANIC(Gx) (for AIS 2+ and AIS 3+ probability of injury) values were 0.29 and 0.364 respectively where the human values at the same injury percentage was 0.56 and 0.72. **DISCUSSION:** The associated injury criteria can be directly applied to ATD safety testing of aircraft ejection or vehicles systems in -Gx accelerative loading to directly translate ATD neck load results to the probability of human injury.

**Keywords:** HMD; pilot; aviation safety; risk curves

## Introduction

Since the discovery of powered manned flight, personal injury hazards have been associated with piloting an aircraft. Several Department of Defense (DoD) weapon platforms have integrated Helmet Mounted Display (HMD) capabilities in an effort to increase the user's operational advantage (Rash et al., 1998). Current systems, like the F-35, have leveraged this technology by incorporating HMDs into preliminary designs. Other designs have simply added the use of non-permanent helmet mounted accessories such as night vision goggles or joint helmet mounted cueing systems like the F-16 and F-18. The additional weight and resultant neck loads imposed by these systems have the potential to increase neck injury risk during ejection.

Numerous neck injury criteria are available and in use today and most use Anthropometric Test Devices (ATD) to test and analyze a myriad of neck loading scenarios. Having an injury assessment tool that can relate ATD-based loading to specific human injury risk is required to quantify the risk associated with fielding aircraft and vehicle systems (Grierson and Dunn, 1995). Grierson and Dunn predicted that the proposed injury evaluation system solution may consist of an instrumented manikin (ATD), a human injury criterion, and manikin to human correlations. In the DoD, instrumented ATDs are currently used to gather force and moment data during accelerative testing. Formulating this data, a human-based neck injury criterion has been developed that consists of a measurement metric along with a risk function that can aid in predicting injury likelihood. However, ATD to human correlation has yet to be clearly defined for the aviation domain (Bass et al., 2006; Parr et al., 2013; Parr et al., 2014; Parr et al., 2015). The purpose of this paper is to 1) demonstrate a method to define and apply a human to ATD transfer function, and 2) to use the transfer function as a method for converting ATD to human MANIC(Gx) values that can be evaluated using existing human risk functions, making them directly applicable to testing with ATDs (Parr et al., 2013).

The most widely used neck injury criteria is the Nij developed for the automotive industry. The National Highway Traffic Safety Administration (NHTSA) has developed an ATD-based neck injury criterion that has been used to assess acceleration limitations and prevent neck injury (Eppinger et al., 1999; Eppinger, Sun, Kuppa, & Saul, 2000). The Nij was formulated to evaluate injury risk in frontal automotive crashes with shoulder belt restrained test subjects. A standardized test subject, the Hybrid-III ATD, was used by the NHTSA for many years to evaluate the neck load response in these frontal impact studies (-Gx impulses). NHTSA uses Hybrid-III ATD tests and associated Nij risk curves to set acceptable neck loading levels in car restraint and airbag systems. This method is a quantitative system for evaluating vehicle safety systems where the observed neck loading metric is related to the likelihood of injury in specified severity categories (FMVSS No. 208, 1999).

It may not be evident that aircraft ejection would expose a pilot or manikin to -Gx (frontal impact) forces similar to Nij input forces. However, due an ejection's dynamic nature, -Gx loading can occur multiple times during a single ejection. Aircrew are exposed to four defined phases and four distinct loading conditions when ejecting, including: 1) catapult stroke exposing the pilot to compressive force in the +Gz direction,

2) windblast, exposing the pilot to a significant -Gx force resulting in neck flexion and tension, 3) Seat stabilization, exposing the pilot multiple forces by small rocket motors to provide attitude adjustments and get the ejection seat into a safe seat-separation orientation, 4) wind drag/drogue chute – produces –Gx forces, 5) parachute opening shock produces a resultant force vector in -Gx and +Gz directions. It has also been shown that the forces associated with neck injuries often occur at one of the most fragile parts of the neck, the cervical spine. (Salzar et al., 2009)

The escape system oversight office of the Air Force Life Cycle Management Center (AFLCMC), which sets specifications for all USAF aircraft acquisition programs, is currently seeking a comprehensive multi-axial neck injury criterion for use in testing and evaluation of escape systems (White JE. Personal Communication; May 2012). Neck injury quantification techniques that are presently used are an insufficient means of fully capturing neck loading during ejection. A human based neck injury criterion with a similar structure to the Nij (called the Multi-Axial Neck Injury Criteria in –Gx or MANIC(Gx)) has been developed and used to evaluate neck injury risk from -Gx accelerations in an aircraft specific context (Parr et al., 2013). Although accelerative inputs that are being evaluated by the MANIC(Gx) are imposed on a subject to induce a -Gx response, the criterion has been defined by MANIC(Gx), a nomenclature change intended for ease of understanding. The criterion developed by Parr et al. uses a mathematical formulation equivalent to the Nij, but is based upon risk curves from human and post mortem human subject (PMHS) data. Thus, this metric will be referred to as the MANIC(Gx) to distinguish it from NHTSA's Nij.

The MANIC(Gx) neck injury criterion was applied to existing human and ATD data from the Air Force Research Laboratory's Warfighter Interface Division's (711$^{th}$ HPW/RHC) biodynamic database along with PMHS data from the literature. First, comparison of human MANIC(Gx) and ATD MANIC(Gx) across a broad range of accelerative inputs will be accomplished to gain a more comprehensive understanding of the relationship between ATD and human subject (combined live and PMHS) neck loads. Second, the observed differences in human and ATD MANIC(Gx) response will be used as a transfer function to develop a method to directly apply ATD test results to human risk curves. Testing directly with ATDs and applying the results to human injury is the anticipated result of this research. This line of research hopes to answer the following research questions:

1. What is the difference in expected MANIC(Gx) between human/PMHS and ATDs over the range of -Gx accelerative input observed from previous laboratory experiments?
2. Can the observed differences in peak MANIC(Gx) be used as a transfer function to make the Parr et al. human-based risk functions and associated neck injury criterion directly applicable for use in testing with ATDs?

**Background**

The MANIC(Gx) neck injury criterion and its associated risk curves have been developed in previous research (Parr et al., 2013). Two separate aviation specific MANIC(Gx) risk functions at Abbreviated Injury Scale (AIS) levels AIS 2+ and AIS 3+ were created from combined human-subject (non-injurious) and PMHS (both non-injurious and injurious) data.  The AFLCMC escape system oversight office is concerned primarily with AIS 2+ injury levels, however this paper will use the same two human risk curves (AIS 2+ and 3+) as Parr et al. (2013) to allow for comparison between the human and ATD probability of injury at AIS 2+ and AIS 3+ levels, and to provide practitioners flexibility to limit risk at injury levels appropriate for their domain specific applications.

**Equation 4.  MANIC(Gx) Neck Injury Criteria Formulation (–Gx Inputs)**

$$MANIC(Gx) = \left|\frac{F_z}{F_{Int}}\right| + \left|\frac{M_y}{M_{Int}}\right|$$

A model presented by Klinich utilizes the four injury mechanisms under review (tension  +Fz, compression - Fz, flexion  +My, and extension  -My) into a single calculation to quantify these forces as shown in Equation 4 (Klinich, Saul, Auguste, Backaitis, & Klienberger, 1996).  This method utilized previous neck tolerance calculations (Mertz and Patrick 1971; Mertz et al., 1978; Nyquist et al., 1980) that provide critical values (also called intercept values) for neck strength in  Fz and My, labeled $F_{int}$ and $M_{int}$ respectively, to normalize the data and allow for scaling of the data to a wide anthropomorphic range.

The current neck tension limits for a Hybrid III 50% male ATD were established by Mertz and Nyquist during separate experiments. Mertz calculated the compression tolerance by recording neck reaction loads when football players struck tackling blocks (Mertz et al., 1978) . The recorded peak value was 4000 Newton’s (N). Nyquist utilized a correlation approach that compared field injury with re-constructed crash tests resulting in tension and shear values to be 3300 N and 3000 N respectively (Kleinberger, Sun, Eppinger, Kuppa, & Saul, 1998). For forward and backward bending moment (flexion/extension) limit creation, Mertz utilized human volunteers and PMHS on a sled test. The humans were evaluated at increasing -Gx levels until neck pain was indicated, the PMHS subjects extended the -Gx range until neck damage was observed to provide the current bending moment limits of 42 ft-lbs. for extension and 140 ft-lbs. for flexion. Additionally, axial tension experiments have concluded that evaluation of intact (whole) PMHS specimens result in a higher mean tension neck failure value than isolated (potted) specimens, Yoganandan et al., and Shea et al. postulated that the presence of an extension moment would significantly affect the tensile strength during neck loading (Yoganandan et al., 1996; Shea et al.1992). The Nij was developed to account for and evaluate these combined loading factors, using critical values ($-Fz_{int}$ for compression, $+Fz_{int}$ for tension, $-My_{int}$ for extension, $+My_{int}$ for flexion) to normalize for anthropometric differences shown in Table 5 (Eppinger et al., 1999, 2000).

The Nij and similar evaluation criterion have been proposed for use in a military application to assess ejection forces (tension and flexion) imparted onto aircrew. The method that NHTSA used to correlate force into an injury prediction value was through the use of logistic regression and associated risk curves. Risk curve generation has been used to evaluate neck injury during ejection, through methods similar to the automotive industry. ATD to human comparison is an essential part of the NHTSA Nij risk assessment. A similar method for use in ejection evaluation would be instrumental in the design and testing of escapes systems, particularly systems that incorporate an HMD and add additional weight that must be supported by the pilot.

The form of MANIC(Gx) is similar to the widely used Nij for calculation of -Gx neck loads, but the risk curves associated with it are significantly different (Parr et al., 2013). MANIC(Gx) risk curves (AIS 2 and AIS3) will be used to evaluate the human and ATD response in an effort to answer the research questions previously stated. Similar input forces are present in both criteria. Additionally the critical (intercept) values that were used in the Parr et al. (2013) article are defined in the Nichols NIC criteria paper (Nichols, 2006) will be used here.

**Table 5. MANIC(Gx) Critical Values**

| | Small:<br>96-135 lbs. | Mid-Size:<br>136-199 lbs. | Large:<br>200-245+ lbs. |
|---|---|---|---|
| Tension (lb.) ($+F_z$) | 964 | 1530 | 1847 |
| Compression (lb.) ($-F_z$) | 872 | 1385 | 1673 |
| Flexion (in-lb.) ($+M_y$) | 1372 | 2744 | 3673 |
| Extension (in-lb.) ($-M_y$) | 593 | 1195 | 1584 |

Injury classification is also an important component of neck injury criteria. The AIS is currently used by a diverse group of biomechanics and kinematic researchers (AAM, 2008). It provides a standard scale for injury classification according to observed severity. These ordinal injury scales are utilized in the MANIC(Gx) (ejection domain) to limit injury to acceptable levels such that the pilot may be able to escape or evade enemy forces upon ejection if required or to navigate to an extraction point. If the accelerative forces are so extreme that the probability of strained ligaments (AIS 2) or vertebrae fracture (AIS 3) are high, then an appropriate injury prediction can be assigned. This process has been demonstrated in previous research to be effective and tailorable to situational conditions (Eppinger et al. 2000; Parr et al. 2013; Cheng et al.,1982, Buhrman et al., 2000 ) The AIS has been used by NHTSA, and other neck injury researchers have also used it extensively. It provides researchers a severity scale that classifies each injury according to its severity on an ordinal 6-point scale with the least severe injury labeled AIS 1 and the most severe listed as an AIS 6. (AAM, 2008) The AIS provides a means for scoping analysis efforts as well as a precise way to present injury data to decision makers once it has been analyzed. Limiting ejection injuries to below AIS 2 or AIS 3 levels is common in USAF risk analysis; therefore these levels are commonly used in aviation specific neck injury criteria.

During ejection a human neck is exposed to multiple accelerative forces that may cause injury, or in the most extreme conditions, ligament tears, neck dislocation, vertebrae fracture and death. The ability to understand and quantify these forces will help provide a decision maker with a reliable, data driven representation of human injury risk. Based on previous human testing, sled testing limitations for humans is roughly 10G. This limiting factor has created a need for a surrogate at higher G levels. PMHS have been used for comparison and evaluation in previous research (Beeman et al., 2013; Salzar et al., 2009). Measures have to be taken to ensure representativeness when testing with a human surrogate. A PMHS does not have the ability to strain under load. In this case it is assumed that the impact force is so sudden that human bracing factors can be removed from this analysis.

Others have evaluated the stability of the lower neck in previous studies and found that the lower neck has a greater ability to support impact forces due to its increase in vertebrae size and general neck musculature that is present across the anthropometric range. Therefore, the upper neck is the point of focus in this research. The Occipital Condyle (OC) is the point at which the head rotates about the neck in the sagittal plane. When accelerated in a -Gx direction, the head mimics a frontal impact trajectory and places a moment force on the OC joint. Ejecting from an aircraft that is moving at a high rate of speed (e.g. 400+ Knots Equivalent Air Seed or KEAS) first exposes the pilot to neck compression (-Fz) in the catapult phase, which turns quickly into frontal impact during the windblast phase. A pilot suddenly experiences the neck moment force that has been previously explained during windblast. In addition to the moment (My) force, a tension force (+Fz) is created by the wind force simultaneously pushing up on the base of the helmet. This combined loading has been found to significantly increase potential neck injury compared to single mode loading.

NHTSA developed risk curves using logistic regression by paired testing of porcine subjects and ATDs, comparing the porcine injury incidences and ATD neck load data. This paired data was scaled and used to develop human injury limitations. AIS specific injury risk functions were created by NHTSA for human injury evaluation. Injury limitations were set at a 22% chance of AIS 3 or greater neck injury, corresponding to an Nij of 1.0. Any -Gx test that was conducted where Hybrid III ATDs exceeded 1.0 was considered a failure (Eppinger et al., 1999). Parametric Survival analysis risk curves have been created and compared to NHTSA risk curves. The NHTSA AIS 2 risk curve has a y-intercept of 11.3%, essentially predicting an 11.3% risk of AIS 2 injury at an Nij of 0. Therefore the NHTSA AIS 2+ curves are not acceptable for evaluation of the 5% risk of AIS 2+ limit imposed by the AFLCMC escape systems oversight office. The human AIS 2+ curve developed by Parr indicated a 5% injury risk corresponding to a 0.56 MANIC(Gx) value, a more accurate and precise criterion for use in evaluating the USAF limits in the ejection environment (Parr et al., 2013).

Parr et al. (2013) created human risk curves for AIS 2+ and AIS 3+ levels using human and PMHS (human representative) data and evaluated them against existing NHTSA Hybrid III ATD risk curves. The human risk curves, limited by a small PMHS test set (N=6), were compared to NHTSA risk curves and found to be more representative for lower Nij values; the NHTSA curves indicated elevated injury prediction at low Nij values. The correlation of human risk curves to ATD response was a concern of Parr et al (2013). This paper attempts to quantify that correlation. The Nij criteria construct was found to be a suitable formulation for -Gx escape system evaluation (MANIC(Gx)). The Nij accounts for anthropometric differences and it has attributes associated that link probability of injury with neck response in frontal impact. When compared to the Nij, the MANIC(Gx) risk functions were assessed to be a more appropriate tool for aviation applications (Parr et al., 2013).

## Methods

### Subjects

Test data used for this analysis was collected from the USAF Biodynamics databank (BIODYN), a part of the Collaborative Biomechanics Data Network (CBDN) which is operated and maintained by the Human Effectiveness Directorate at Wright-Patterson Air Force Base, OH (WPAFB). All tests were conducted at Air Force Research Laboratory's Warfighter Interface Division's (711$^{th}$ HPW/RHC) Horizontal Impact Accelerator (HIA) at WPAFB. The acceleration profile was a half-sine pulse with 65ms of rise time and 150ms duration for both human subject and ATD testing. Data from previous human and ATD testing was used. The tests focused on neck response when exposed to a -Gx impulse force, a similar mode of acceleration as windblast. The choice to use multiple ATD types and sizes was made to evaluate the MANIC(Gx) across a wide anthropometric range.

Two data sets were used to complete the methods described in this chapter. The first data set consisted of 67 humans who were accelerated at either 6 or 8 G. The second data set consisted of 6 PMHS. The PMHS data was used for the injurious testing (32-39G) and a 67 human set used for the non-injurious points, these data were aggregated to create a new combined "human" data set for evaluation. Henceforth the term 'human data set' will refer to the combined human/PMHS data as described above.

Human subject testing consisted of each volunteer being fit with appropriate restraint harnesses, a HGU-55/P flight helmet, and MBU-12/P oxygen mask. All subjects were accelerated while restrained in an ACES-II ejection seat. The protocol for this testing directed test subjects to “brace”, a training technique for pilots that is thought to reduce neck injury by forcing the head toward the head rest of the seat. The seat was attached to the sled track and accelerated to collect human response data. The human subjects were fitted with a sensor package that consisted of a bite bar fitted with triaxial linear accelerometers and an angular accelerometer to measure head accelerations. Data was collected for the entire run time however, to reduce erroneous values only the initial accelerative input portion (~200 ms) was used for the calculation of peak MANIC(Gx). No human test points resulted in significant neck injury (>AIS 1) although approximately 15% did notice neck stiffness or soreness, none of which resulted in any clinical diagnosis (Parr et al., 2013). The peak resultant MANIC(Gx) values were calculated using observed accelerations and subject head and neck mass following methods that have been employed in previous research (Doczy et al., 2004; Gallagher et al. 2007). MANIC(Gx) was only observed for the initial acceleration and not for the residual accelerations that resulted from sled deceleration.

The human data used in this study was also used in the research conducted by Parr et al. (2013). This data consisted of non-injurious human neck response to -Gx accelerations between 6 and 10 G’s. The human subjects’ weights ranged from 119-276 lbs. The human subjects were fitted with a bite bar and instrumented helmet apparatus for data recording purposes. Acceleration data from the accelerometers on the bite bar were used to calculate tension (+Fz) and flexion (+My) forces at the occipital condyle for use in the MANIC(Gx) calculations according to methods outlined by Parr et al. (2013). Additionally, data from experiments with 6 PMHS was used in linear regression analysis as the high G points. The PMHS weight ranged from 110-211 lbs. and the test sled input (-Gx) accelerations ranged from 32-39 G's. The PMHS MANIC(Gx) values were calculated using peak values for axial loading and bending moment. These two forces were recorded separately with no time history, resulting in the forces most likely not happening at the same time, this is a deviation from the normal MANIC (Gx) approach of using time matched forces to ascertain time specific peak observed MANIC(Gx). The MANIC(Gx) values were calculated with the NHTSA Nij intercept values from Table 3 (Eppinger et al., 2000), where occupants less than 63.5 kg use small-sized female intercept, the mid-sized male intercept was used for body mass between 63.6-90 kg, and the large male intercept used when the occupant was greater than 90kg. Because the PMHS MANIC(Gx) calculation methods described above did not allow for the use of time paired data points in the calculation, the resulting MANIC(Gx) values are potentially higher than they would be if peak instantaneous load data were available (Cheng et al., 1982). The PMHS data collection and MANIC(Gx) calculation specifics are available in the research of Cheng et al. and Parr et al. (Cheng et al, 1982; Parr et al., 2013). These two data sets were combined and a linear regression model was fitted, with human data representing neck response below 10 G's and the PMHS data representing neck forces experienced when accelerated above 10 G's.

The ATD data is comprised of three separate -Gx accelerative input tests conducted using the Horizontal Impulse Accelerator (HIA) at the Air Force Research Laboratory's Warfighter Interface Division (711th HPW/RHC) at WPAFB. First, the low G data (see Table 6) consisted of ATDs that were placed under 6-10G impact accelerations as a paired comparison set for the previously discussed human low G testing. The second set of ATDs were tested at high G levels in an attempt to characterize neck response for a newly developed aviation specific ATD, the Advanced Dynamic Anthropomorphic Manikin (ADAM). The third data set, from another high G study, was used as part of the Joint Primary Aircraft Training System (JPATS) development, a standardized DoD ATD testing apparatus. Both the ADAM and JPATS input accelerations ranged from 20-45G. Two JPATS variants were used in the study, one Small JPATS and one Large JPATS weighing 116 lbs. and 218 lbs. respectively, representing the majority of the AF acceptable weight range. JPATS are modified Hybrid III manikins, while ADAM was a ground-up development for aviation use; both used versions of the Hybrid III neck. The Hybrid III neck is currently considered the state of the art for -Gx accelerative force testing. All three experiments followed similar test procedures however the seat angles in some test configurations varied from zero to 30° in some cases. Due to the nature of the small PMHS and limited high-G ATD test data pool the effects of seat recline when calculating MANIC(Gx) levels were assumed as negligible. The critical data for this research was internal neck Fx and My forces collected from 19 unique ATD tests to calculate the MANIC(Gx). The 19 test data sets were pulled from the two separate studies and were comprised of 11 ADAM tests (9 Small, 2 Large) and 8 JPATS tests (7 Small, 1 Large).

**Table 6. ATD Test Parameters**

| Acceleration (-Gx) | Size -Lbs. | ATD Type | Peak MANIC(Gx) |
|---|---|---|---|
| Study #199301 | | | |
| 6 | 218 | ADAM-L | 0.0825 |
| 6 | 218 | ADAM-L | 0.0859 |
| 6 | 218 | ADAM-L | 0.0737 |
| 7 | 218 | ADAM-L | 0.0701 |
| 7 | 218 | ADAM-L | 0.0669 |
| 7 | 218 | ADAM-L | 0.0688 |
| 8 | 218 | ADAM-L | 0.0995 |
| 8 | 218 | ADAM-L | 0.0996 |
| 8 | 218 | ADAM-L | 0.0986 |
| 10 | 218 | ADAM-L | 0.1188 |
| 10 | 218 | ADAM-L | 0.1317 |
| 10 | 218 | ADAM-L | 0.1374 |
| Study # 199201 | | | |
| 20 | 145 | ADAM-S | 0.583 |
| 20 | 145 | ADAM-S | 0.625 |
| 20 | 145 | ADAM-S | 0.689 |
| 35 | 145 | ADAM-S | 0.631 |
| 35 | 145 | ADAM-S | 0.448 |
| 35 | 145 | ADAM-S | 0.999 |
| 45 | 145 | ADAM-S | 0.708 |
| 45 | 145 | ADAM-S | 0.792 |
| 45 | 145 | ADAM-S | 0.883 |
| Study # 199501 | | | |
| 20 | 116 | JPAT-S | 0.516 |
| 20 | 247 | JPAT-L | 0.34 |
| 20 | 116 | JPAT-S | 0.43 |
| 30 | 218 | ADAM-L | 0.876 |
| 30 | 218 | ADAM-L | 0.524 |
| 30 | 116 | JPAT-S | 0.441 |
| 35 | 116 | JPAT-S | 0.894 |
| 35 | 116 | JPAT-S | 0.957 |
| 40 | 116 | JPAT-S | 0.535 |
| 45 | 116 | JPAT-S | 0.425 |

Both study configurations were similar. One of the JPATS study objectives was to relate the JPATS dynamic response to ADAM's, under comparable loadings. Similar to the human test setup, all ATDs wore a HGU-55/P flight helmet or equivalent and an MBU-12/P oxygen mask for each test run (Buhrman, 1996). ADAM and JPATS ATD's, were each configured with a six-axis neck load cell and a tri-axial head accelerometer as a minimum, along with other data acquisition transducers located at other study specific points of interest. Refer to the study documentation for further information (Doczy et al., 2004; Variable Weighted Helmet Gx Study, 2004)

**Procedures**

The MANIC(Gx) was calculated using raw neck force and moment (Fz and My) data from the load cells in the neck of each ATD and human neck forces calculated as described by Parr et al. using human subject head mass and recorded linear and angular accelerations (Parr et al., 2013). The human subject MANIC(Gx) was calculated at each time interval over the time history of each test using the MANIC(Gx) formula from Equation 1, with the peak values being recorded. The PMHS MANIC(Gx) values were calculated using overall peak force and peak moment data, since time history data was not available from the original study (Cheng et al., 1982). . The intercept values in Table 3 were used based on subject weight (human, PMHS, and ATD). The single peak MANIC(Gx) values for each subject were used for linear regression analysis.

**Statistical Analysis**

JMP Version 12 statistical software was used to analyze the data (SAS, 2015). Linear regression of peak MANIC(Gx) was the variable of interest (dependent variable), the calculated MANIC(Gx) was evaluated against accelerative input (independent variable) for both the human data and the combined ATD data to create two regression models. The first regression line was created using ATD data that varied in weight from 116-245 lbs. The second regression line was built by using the existing human data comprised of both human subjects and PMHS data, where subjects weighed from 110-211 lbs. The peak MANIC(Gx) data points were recorded for each test and plotted against the respective accelerative input (E.g., 6, 8,…45 G). A regression through the origin technique was employed for the human data since it can be reasonably assumed that when acceleration (independent variable) is not present, the MANIC(Gx) value (dependent variable) will be zero. ATD linear regression results were already indicative of this assumption and did not use regression through the origin procedures. This approach does make some statistical fit models value inaccurate however. It also should be noted that any interpretation or extrapolation of the line extending past the observed data points should be avoided. The expected value equation for human and ATD MANIC(Gx) were both plotted for comparative purposes, refer to Table 4 for more detail.

**ATD Adjusted Metric Development**

The difference between ATD and human linear regression lines at each G level was calculated and used as the basis of an ATD to human MANIC(Gx) transfer function. The human AIS 2 and AIS 3 risk functions were used for attaining human MANIC(Gx) values that correspond to 5, 10 and 22% risk. The human MANIC(Gx) values at these levels were recorded and used in conjunction with the linear regression model to find the

G level where the human MANIC(Gx) occurs, the human MANIC(Gx) at each significant risk level are shown in Table 7 and Table 8. Using that G level and the ATD linear regression model, an ATD-transformed MANIC(Gx) value is found. After both ATD and Human MANIC(Gx) levels were recorded they were compared using the human risk function curves where human MANIC(Gx) and injury levels are observable. The ATD MANIC(Gx) can be looked up using the human risk function and a human injury probability may be assigned to that ATD-transformed value based on its calculated MANIC(Gx) level.

**Results**

The linear regression analysis used in this research resulted in an observable difference between the ATD and the human/PMHS MANIC(Gx) over the range of accelerative input studied. Figure 10 shows the differences by plotting the regression model's equations across a relevant range of -Gx input acceleration values. The plotted data points indicate an elevated response (higher MANIC(Gx)) seen by the human throughout the entirety of the range. The ATD-transformed MANIC(Gx) values were recorded at the G level where human MANIC(Gx) values correspond to 5, 10 and 22% injury on the previously developed human risk function plots. Those ATD transformed MANIC(Gx) values from the linear regression were carried forward to the human risk functions (AIS 2 and AIS 3 Curves) for specific injury probability assignment.

**Table 7. Human AIS 2+ comparison of human and ATD-transformed MANIC(Gx) values and associated injury risk levels**

| AIS 2+ P(Injury) | Human MANIC (Gx) | G Level | ATD-transformed MANIC(Gx) @ Human G Level |
|---|---|---|---|
| 5% | 0.56 | 14 | 0.29 |
| 10% | 0.75 | 18.7 | 0.377 |
| 22% | 0.97 | 24.2 | 0.474 |

**Table 8. Human AIS 3+ Comparison of human and ATD-transformed MANIC(Gx) values and associated injury risk levels**

| AIS 3+ P(Injury) | Human MANIC (Gx) | G Level | ATD-transformed MANIC(Gx) @ Human G Level |
|---|---|---|---|
| 5% | 0.72 | 18 | 0.364 |
| 10% | 0.95 | 23.7 | 0.465 |
| 22% | 1.23 | 30.7 | 0.59 |

The following scenario demonstrates the application of this method to an example real world safety evaluation test using at ATD. During ATD -Gx testing at 20 G accelerations the observed Fz and My time history values are used to calculate a peak

MANIC(Gx) value of 0.65. Since this value is related to observed ATD response, without additional products or metrics it cannot be used as an indicator of human injury. If the linear regression model from Figure 10 is used as a lookup table or transfer function, this ATD MANIC(Gx) value of 0.65 can be linked to a G level required to induce this response based on the linear average intersection point. In this case that ATD MANIC(Gx) value would be achieved at or near 34.1 G's in the -x axis. Using this G level we can find the average MANIC(Gx) value associated with a 34.1 G input on the linear regression model (Figure 10). The equivalent human response at 34.1G results in a 1.36 MANIC(Gx) value which, based on existing human risk curves corresponds to a 57.9% of AIS 2+ injury.

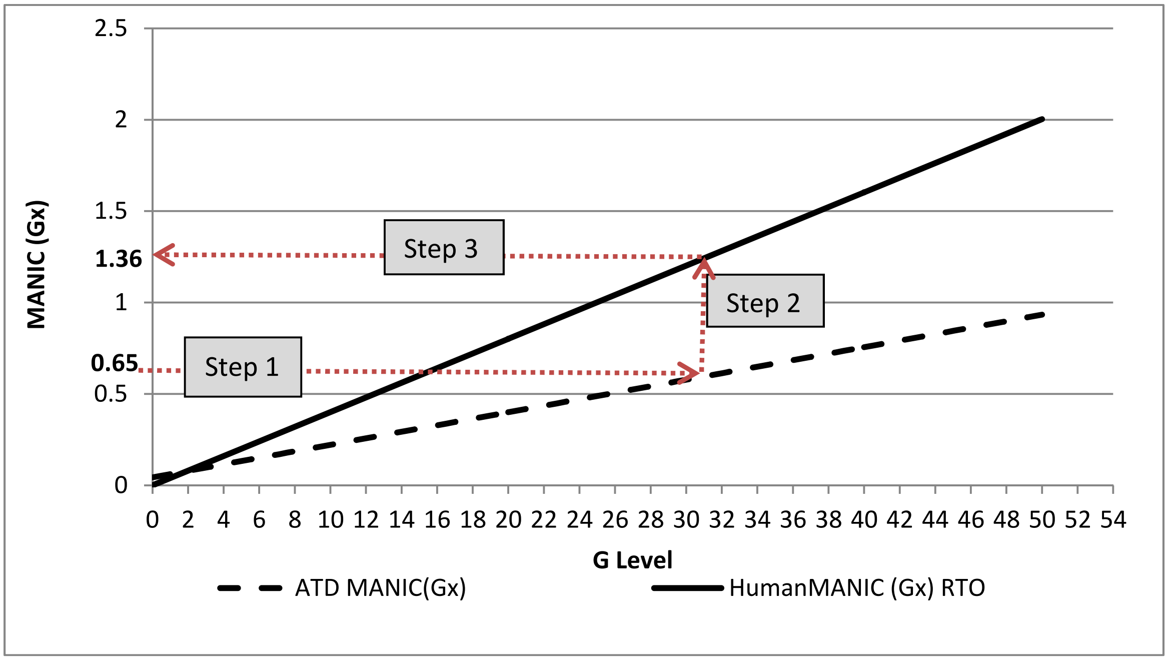


**Figure 10. ATD and Human MANIC(Gx) Linear Regression Model of Expected Values Across Accelerative Inputs**

Previous aviation neck injury criteria studies that produced risk curves have used Minitab and SA that account for left and right censored data (Parr et al., 2013). As noted previously, the USAF desires to limit ejection injury probability of AIS 2 or greater to a 5% risk. Human risk curves at AIS 2+ and AIS 3+ levels have been created previously. The equations of the human AIS 2+ and AIS 3+ risk functions generated by the SA are shown in Equation 5 and **Equation** 6 respectively. These equations were used previously to develop human risk curves created by Parr et al (refer to Figure 11**)**. A similar process will be used for predicting human injury by evaluating the ATD test data and using the transfer methods described above to link the ATD neck response (MANIC(Gx)) to human injury based on the difference in MANIC(Gx) observed at the same acceleration (G) level. The ATD and human MANIC (Gx) linear regression functions provide an average (expected response) and are used as a predictor when attempting to find MANIC(Gx) values for a test subject being exposed to similar inputs.

Having the linear regression model at hand when performing ATD system level testing will enable a test engineer to look at the data and quickly associate the ATD MANIC(Gx) scores to human MANIC(Gx) scores and assign an injury probability that could be assumed if a human were exposed to a test of similar –Gx acceleration.

**Equation 5. Probability of AIS 2+ Neck Injury (Parr et al., 2013)**

$$P(\mathrm{AIS} \geq 2) = \frac{1}{1 + e^{\left(\frac{1.422819 - \mathrm{MANIC(Gx)}}{0.261532}\right)}}$$

**Equation 6. Probability of AIS 3+ Neck Injury (Parr et al., 2013))**

$$P(\text{AIS} \geq 3) = \frac{1}{1 + e^{\left(\frac{1.746944 - \text{MANIC(GX)}}{0.313913}\right)}}$$

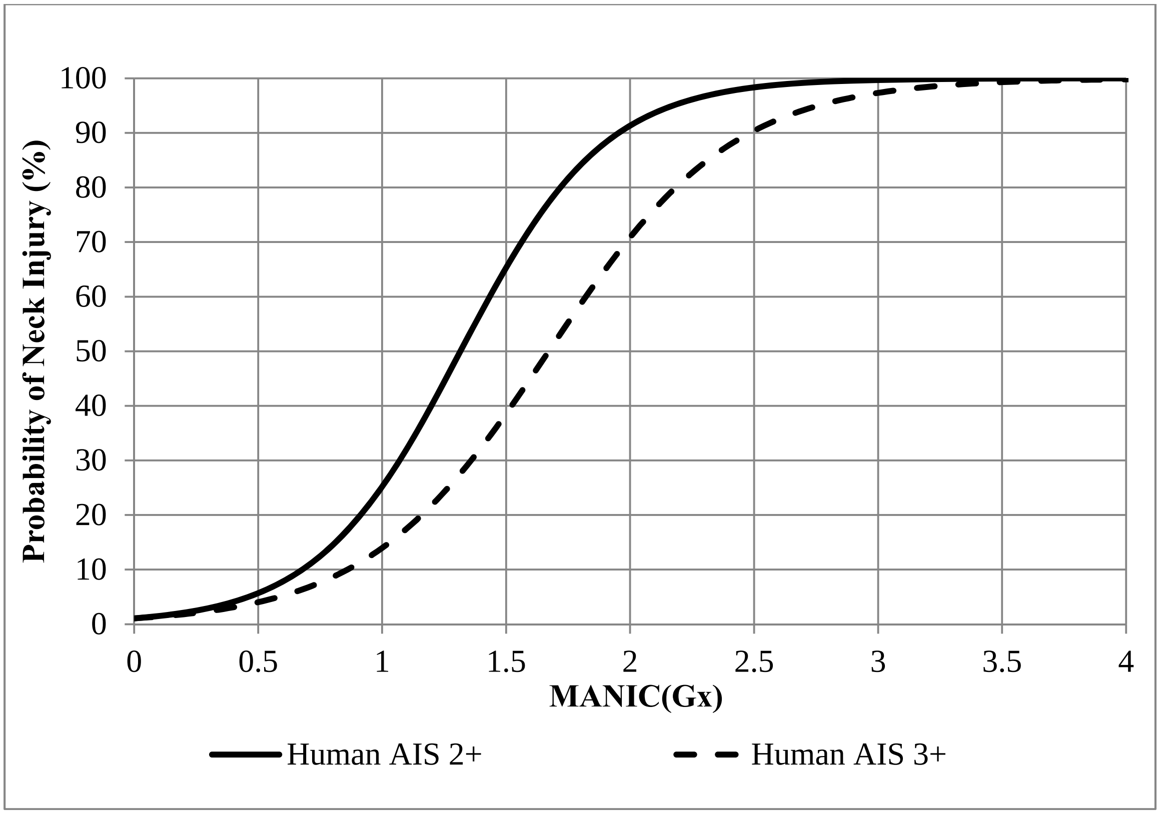


**Figure 11. Human AIS 2+ and AIS 3+ Risk Curves (Parr et al., 2013)**

A noticeable difference between the ATD and human injury probability was observed. Particular differences in MANIC(Gx) and probability of injury were observed when keeping G level constant. Noticeably, a 5% AIS 2+ human injury would equate to an ATD MANIC(Gx) value of 0.29 where in human tests it has indicated at 056. The probability of injury in this case drops from the AFLCMC limit of 5% to a mere 1.69% injury associated with the ATD MANIC(Gx) level. A full list of AIS 2 and AIS 3 values are located in (Table 7, Table 8 and Table 9). In Table 7and Table 8, ATD-transformed and human MANIC(Gx) predicted values at 5%, 10%, and 22% probability of injury can be directly compared. The 22% probability of injury level on the AIS 3+ curve is representative of NHTSA Nij limits. The 5% probability of injury level is a USAF limitation that has been set for use in ejection testing. The10% probability of injury has been used in previous neck injury criteria (NIC) and is also included in this analysis. The NHTSA AIS 2+ risk curve intercepts the vertical axis at 11.2% probability of injury leaving voids in Table 9 at the NHTSA AIS 2+ 5% and 10% probability of injury rows.

**Table 9. MANIC(Gx) Predicted Values at 5%, 10% and 22% Probability of Injury for Human, ATD-adjusted, and NHTSA risk curves**

| | Human | | ATD-transferred | | NHTSA | |
|---|---|---|---|---|---|---|
| P(Injury) | AIS 2+ | AIS 3+ | AIS 2+ | AIS 3+ | AIS 2+ | AIS 3+ |
| 5% | 0.56 | 0.72 | 0.29 | 0.364 | N/A | 0.114 |
| 10% | 0.75 | 0.95 | 0.377 | .465 | N/A | 0.562 |
| 22% | 0.97 | 1.23 | 0.474 | 0.59 | 0.66 | 1.0 |

The previously developed human MANIC(Gx) limits at 5%, 10%, and 22% probability of injury from Parr et al. shown in Table 9 indicate an AIS 2+ 5% predicted injury value of 0.56 and an AIS 3+ 5% predicted injury value of 0.72 (Parr et al., 2013). The ATD limits also displayed in Table 9**,** resulted in a 5% predicted AIS 2+ injury at a 0.29 MANIC(Gx) value and a 5% predicted AIS 3+ injury at a 0.364 MANIC(Gx) value. The ATD transformed MANIC (Gx) levels when G level is kept constant, are approximately half of the human MANIC(Gx) values across the range of injury probability listed in Table 7 and Table 8. It can be assumed that any MANIC(Gx) level above 2.0 indicate a very intense acceleration and according to these adjusted risk curves, could contribute to AIS 2+ neck injury in more than 90% of the cases. An AIS 3+ injury is indicated to occur more than 70% of the time above a MANIC(Gx) value of 2.0.

**Discussion**

The Nij and MANIC(Gx) criteria account for anthropometric differences by use of critical intercept values and are identical in formulation. Being able to use these criteria to predict human injury risk probabilities by using ATD test data provides a basis of discussion for ATD to human injury probability metrics. ATDs and human subjects are not completely biofidelic of one another in testing environments (Buhrman and Perry, 1994). For instance, ATDs initiate head and neck movement prior to the point where similar human subjects do and later than similar PMHS when under similar loading (Beeman et al., 2012; Beeman et al., 2013). Likely due to ATD neck design, the ability of human subjects to brace under loading and the lack of neck stability in PMHS. This may explain the elevated linear regression function where human (PMHS) MANIC(Gx) levels were higher than the ATD MANIC(Gx) levels above 2 G.

Historically ATDs have been created and used in an effort to spare humans from injury during escape system testing. Creating a test surrogate that would respond identically in a wide variety of input conditions would be ideal; however it is unlikely due to the complex structure and interdependencies of human anatomy. In the absence of a perfect surrogate, developing a human to ATD transfer function is required. The next best course of action is using ATDs as a test subject that is capable of indicating human injury risk.

This research was limited by the amount of available PMHS -Gx neck force data. More PMHS data that focuses on -Gx acceleration and captures the data required calculate the MANIC(Gx) is necessary for additional axis risk function development. The current PMHS data (N=6) used for this analysis was limited by lack of accelerative input between 10G (human limit) and 32 G, where PMHS data began. Incorporating additional PMHS data over these mid-range accelerative inputs would significantly raise confidence in the linear regression and thus the overall transfer function method. Having these points could also be useful for validating existing human injury risk functions. Future experiments should include controlled testing of humans/PMHS and ATDs with head supported mass to capture the neck loads generated by acceleration combined with head supported mass. Based upon the MANIC(Gx) neck criteria, and the information that was depicted in Parr et al. showing the differences between Nij and MANIC(Gx) in an aviation specified environment (head borne weight), more effort should be placed into the investigation of ATD neck response and how it is related to human neck response in the other accelerative planes (Gy and Gz). Future research should also attempt to procure more ATD neck response data adding to the databank and increasing sample size for future analysis and validating the linear regression results presented here. The ATD and human data may provide a different result in future work as new data is collected and added to the analysis. Comparing multiple human and ATD data sets to refine the ATD to human transfer function will be an iterative process and limited by the availability of test results.  Having a databank of multi-axial test results will provide an opportunity for comparison across all axes and further validate these human to ATD relationship findings.

# V. Conclusions and Recommendations

## Chapter Overview

The material presented in this thesis was organized in a scholarly format that incorporates a conference paper that has been accepted to the 2016 Industrial & Systems Engineering Research Conference and a journal article to be submitted in the Aerospace Medicine and Human Performance journal. This chapter serves as an overall summary of the document starting from the purpose and goals that were listed in Chapter 1. Providing a literature review in Chapter 2 was intended to summarize the pertinent literature covering the current state of the art in the field of injury biomechanics and introduce the previously applied neck injury criteria that have been used in the field. The conference paper in Chapter 3, along with the journal article in Chapter 4 together addresses the research questions that were posed in the introductory chapter. A summary of the findings and suggestions for future research will make up the remainder of this Chapter 5.

## Summary of Research

### Literature overview:

Helmet mounted devices are becoming a ubiquitous part of aviation, and increasingly any DoD operations environment has proclivity for an up-front information interface similar to those that are used in HMDs. The increasing use of HMD technologies provide the user with a more efficient interface to execute their operational tasks, but also causes a greater percentage of aviators to support additional neck borne weight. This situation combined with relaxed minimum weight requirements for pilots combine for a more precarious situation during ejection due to the additional weight supported by a greater variance in neck structure. The importance of developing effective interfaces that increase performance and minimize safety concerns is growing. These factors provide a need to develop and integrate HMDs with the end user in mind. Part of the life cycle of HMD technologies that are being developed is testing and evaluation, currently accomplished by use of ATDs and limited human and PMHS testing. Human injury prediction and characterizing risk is the purpose of neck injury testing and this research lined up with these goals. Attempting to characterize risk in a highly dynamic ejection environment is complicated and cannot be taken trivially. Using human and PMHS neck response data to capture and characterize injury probability during ejection is a necessary step that other researchers have focused on. The injury probability data can be incorporated into HMD design and set limiting factors for size and center of gravity in attempt to minimize injury and maximize operational efficiency.

The literature summarized in Chapter 2 has been useful in moving the body of knowledge to where it is today however, the automotive history is evident in most of the approaches. This review revealed that even though ATDs have been used for extensive testing, there have not been significant studies to validate ATD neck response results with human tests. Nor have there been any ATD specific risk functions developed for aviation use due to absence of ATD injury information. Either an analysis of only the compressive forces was used or in most Gx specific research, the direct application of the automotive Nij was applied to an aviation environment. The literature review provided background information that is relevant to the research approaches that were used in this effort and a test case was presented that led to the methods that were discussed in Chapters 3 and 4.

### Research Purpose and Goals

This research centered on the creation of a MANIC(Gx) ATD to human transfer method to use for human injury prediction in conjunction with previously developed human risk functions. Linking human injury to ATD performance while exposed to –Gx accelerative input is very important in the aviation domain during safety and developmental testing. The methodology, creation, evaluation and discussion of the resultant method are accomplished in Chapter 4. While previous research has defined some aviation specific neck injury metrics, an investigation into the -Gx response relationship between ATD and human was required. This evaluation was intended to improve the understanding of the relationship between ATD neck response and human injury. The development of usable ATD -Gx MANIC(Gx) values associated with AIS 2+ and AIS 3+ injury were goals of the research. First the relationship between ATD and human neck response was quantified. This was accomplished through linear regression techniques. The intent of the analysis that took place in Chapter 4 was to answer the investigative questions relating to a -Gx injury criterion development and verification.

### Data Collection

Data from previous -Gx studies was used, consisting of 67 human data points along with six PMHS neck injury points. To develop an ATD to human transfer function, a substantive ATD data set was also required. The data sets used originated from previous ATD testing that used –Gx accelerative input forces. All of the high G -

Gx ATD data was previously collected and available from the USAF AFRL Biodynamics Databank, a component of the Collaborative Biodynamics Data Network. Each ATD and human study used an ejection seat, helmets, oxygen masks and other representative support equipment during accelerative testing.

**Data Arrangement and Analysis**

Multiple data parameters were recorded for each human and ATD study, the data required to evaluate both subject variants was neck tension (+Fx) and neck flexion (+My) forces. The human and PMHS data had to be converted from the bite bar data acquisition apparatus to an applicable force measure through conversion factor calculations. Optimally, a direct force value would be generated when testing human and PMHS. The MANIC(Gx) neck evaluation criterion requires the use of critical values ($F_{int}$ and $M_{int}$) that are anthropometric specific and represent neck failure limits in their respective directions based on body size and subject type. These critical values have been characterized, validated and used by multiple researchers; they were used here in the MANIC (Gx) calculations for ATDs and humans. The PMHS MANIC(Gx) (in the form of Nij) values were previously calculated and required no manipulation for this specific analysis, these reflect elevated MANIC(Gx) values because of how the peak force and moment data were collected. Instead of using time paired force and moment response data to create an instantaneous peak MANIC (Gx), the peak Fx and My from each run were used together, even if they did not occur simultaneously. The 19 high G ATD test sets required MANIC(Gx) to be calculated for direct comparison between ATD and human neck response. The high G ATD data was recorded as time specific data, a peak value was recorded, indicating the time where the combined accelerative neck forces (Fz and My) created a peak MANIC(Gx) value. A peak MANIC value was recorded for each of the 19 tests as well as the peak MANIC(Gx) for each of the human and PMHS tests.

### Data Analysis Results

JMP statistical software was utilized to develop a linear model, using linear regression through the origin techniques. Human and ATD MANIC(Gx) values were plotted across a range of accelerative inputs using the JMP regression equations. Regression through the origin was used in order to accurately capture the response of MANIC(Gx) across the range of accelerative input, an input of zero was included, assuming that the neck loads at zero input would result in a low MANIC(Gx) value. The regression analysis resulted in statistically significant human and ATD lines where the human expected MANIC(Gx) indicated greater values than the ATD MANIC(Gx) results. The ATD and human differences were used to formulate the transfer function that is explained in Chapter 3 and applied in Chapter 4. The transfer function was applied to the combined human and PMHS data set used as input data for the survival analysis. An important step was creation of an ATD transferred MANIC(Gx) that was representative of human injury. Human risk functions were then used for ATD to human injury results and discussion of potential future implications. The following investigative questions were used as the epicenter of the evaluation and discussion.

**Investigative Questions Answered**

*What is the difference in expected MANIC(Gx) between human/PMHS and ATDs over the range of -Gx accelerative input observed from previous laboratory experiments?*

This can be captured by evaluation of the two linear regression models and the plotted data over the same accelerative input range. It was observed that as the level of acceleration increased, so did the difference in MANIC(Gx) between the two. With increasing accelerative input, the human neck response is greater than ATD response. This result is most likely due to the ATD neck stiffness that has been engineered into the device for reliability and repeatability over the course of its useful life. The low G human response is lower than ATD , this result is fairly intuitive in nature and may be to musculature and ability to react to input forces by exerting opposing neck force by bracing, mitigating some of the resultant motion. Once the PMHS data is introduced, it demonstrates higher MANIC levels that sway the linear regression model to produce a greater slope at the higher G accelerations; this may be due to the lack of stability and musculature in the PMHS neck.

*Can the observed differences in human and ATD peak MANIC(Gx) be used as a transfer function to make the Parr et al. human-based risk functions and associated neck injury criterion more appropriate for use in testing with ATDs?*

The observed differences in the linear regression models provided a way to correlate human and ATD MANIC(Gx) values when exposed to the same accelerative input.

The expected neck response was indicated by each regression line and can be used to link the two test subjects.

## Significance of Research

Testing cost accounts for a large portion of any new products development budget. Testing with humans is time consuming, costly and potentially dangerous to the test subjects. These factors are especially important when testing HMD designs at a wide range of accelerative input. The automotive field has utilized strictly ATDs in their frontal crash testing, leading to system evaluation and risk mitigation based on those results. The aviation community seeks to improve upon that by developing a human verified neck injury criterion for use when testing with ATDs. The escape system community is increasingly interested in the results of this research because of the possibility for testing to be conducted using ATDs while providing human risk assessment and helmet design constraints. Having the risk probability difference between the two test entities quantified will allow future ATD test results to be translated to human injury risk at AIS 2+ and AIS 3+ levels. These tools may aid in timelier testing while reducing life cycle costs of HMD development or integration programs.

## Recommendations for Future Work

This study was founded in the correlation of human and ATD response through linear regression. Additional ATD data should be collected and added to the linear regression base of knowledge paying close attention to how any new ATD regression results differ from the original ATD and human/PMHS lines. There were limitations that occurred in this study from limited PMHS -Gx accelerative test data pool and a lack of PMHS neck load data. Additional PMHS testing is a requirement to further the field of study.

The complete MANIC criterion is comprised of Gx, Gy and Gz accelerative inputs and the accompanying risk functions. The Gx portion of that criterion has been addressed in this research however, evaluation of the Gx and Gy planes will be required to form a human validated ATD based multi-axial neck evaluation criterion.

**Final Thoughts**

Military applications of neck injury criteria have been met with mixed results. Aviator safety is of utmost concern when setting neck injury limits, the same can be said when defining requirements for future HMD design. Being able to quantitatively relate ATD to human neck injury will aid in mitigating human injury while justifying HMD requirements. The investigation presented here has demonstrated a method to limit human injury by using instrumented ATD testing results along with existing human risk functions.. The risk functions along with the linear regression model (as a lookup device) provide a potential method to develop a useable tool for -Gx neck evaluation in the future after more human and PMHS data is incorporated into the linear regression. The advancements in aviation technology have created an environment where additional head supported weight is becoming commonplace; a comprehensive evaluation tool will be useful in future development efforts. Demonstrating this method via the MANIC(Gx) (in the –Gx axis of acceleration) was only the first step in the validation process, two axis of evaluation remain. Substantial improvements to the available data will increase the validity of the future research results and allow for a more quantitative, statistical evaluation. This research was the first step in validating an ATD neck injury tool, additional steps are required however, and this investigative effort was effective at demonstrating the merits of this method.

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| 14. ABSTRACT<br>The use of Helmet Mounted Displays is ubiquitous in the field of aviation, adding operational capability, increasing head-supported weight and potential neck injury risk. Developing neck injury criteria to evaluate and quantify neck injury is important to ensure ejection systems are produced within acceptable standards. An ATD to human transfer function is developed that quantifies the difference between ATD and human neck response from -Gx accelerative tests, and demonstrates how this function can be applied to ATD test data to make previously developed human risk functions directly applicable to interpreting ATD data with a human-based neck injury criterion. A difference between the human and ATD MANIC(Gx) neck response was measurable, the ATD indicated lower MANIC(Gx) levels at equivalent AIS risk probabilities. For instance, at 5% probability of neck injury risk, the ATD MANIC(Gx) (for AIS 2+ and AIS 3+ probability of injury) values were 0.29 and 0.364 respectively where the human values at the same injury percentage was 0.56 and 0.72. The associated injury criteria can be directly applied to ATD safety testing of aircraft ejection or vehicles systems in -Gx accelerative loading to directly translate ATD neck load results to the probability of human injury. | | | | | | |
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